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ABSTRACT

This report describes two programs which were developed with National Science Foundation support to enable graduates of the program to function in roles traditionally assigned to physicists, engineers, chemists, and computer scientists but which are primarily mathematical in nature. Graduates of traditional programs in mathematics have had little experience or incentive in applying their mathematical training to real world problems and thus institutions other than colleges have been hesitant to have them. To combat this problem, a graduate program in applied mathematics was developed at Clemson University and Washington State University. The programs at both institutions are described, including course descriptions and formal degree requirements as well as examples of Masters of Science projects. The report closes with brief bibliographies concerning mathematics education and mathematical modeling. (TG)

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NEW OPPORTUNITIES IN Applied Mathematics

A REPORT FROM CLEMSON UNIVERSITY
AND WASHINGTON STATE UNIVERSITY

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OCTOBER 1979

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PREFACE

Clemson and Washington State are universities where interesting things have been happening. With ample support from the National Science Foundation, they have been developing programs that constitute a hopeful and constructive response to contemporary problems in the graduate education of mathematical scientists.

This booklet is a report on their efforts so far. It is addressed primarily to:

a. the National Science Foundation;

b. members of mathematics faculties exploring modes of graduate education alternative to the traditional one;

c. students who want to learn about unusual educational and career opportunities in the mathematical sciences.

One copy is being sent to each U.S. mathematics department which offers a bachelor's degree. While the supply lasts, a copy will also be sent to every individual who requests one. In any event, further information about the two programs may always be obtained by writing to the respective departments; their addresses are on the title page.

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PART I. INTRODUCTION

In recent decades, the great majority of recipients of Ph.D.'s in mathematics have joined faculties of colleges and universities, and their work has consisted primarily of teaching and research. With the discovery, about 1970, that this situation could not continue because of a leveling off of the size of the national mathematics faculty, the future of graduate education in mathematics became a subject of considerable anxiety. Paradoxically, this apparent contraction of prospects came at a time when large numbers of people in government, private management, science, and technology were developing a new respect for and reliance on mathematical methods for attacking many of their urgent problems. This mathematicization of many kinds of activity accompanied, but was by no means limited to, the increasingly pervasive use of computers.

The rising need outside the academic world for mathematically trained people and the declining demand for them inside that world might have been expected to offset each other. It is difficult to assess how far this has happened, but it is quite clear that it has not gone nearly as far as might have been predicted. One major obstacle has been the slowness of most graduate programs to adjust to the changing situation, as evidenced by their continuing to produce considerable numbers of mathematicians who, however excellent by the traditional criteria, were neither oriented toward, nor especially well trained for, nonacademic work. The second, partly a result of the first and partly a result of past disappointments with traditionally trained mathematicians, was nonacademic employers' reluctance to hire people with advanced degrees in mathematics. They often recruited physicists, chemists, engineers, computer scientists, and graduates of business schools to do what was primarily mathematical work.

All too often the industrial image of the mathematician, even of the "applied" mathematician, was of a person who may have had deep training, but was not able or much inclined to communicate with management or with specialists in other fields; was reluctant to dedicate effort to real-world problems, but expected to be allowed or even encouraged to do independent research, often irrelevant to the interests of the organization; and was aloof and unproductive unless amenable to extensive retraining: was, in short, an awkward luxury. The image

may not have been entirely fair—no one would deny that there were many exceptions—but it was widespread.*

In the early seventies the Department of Mathematical Sciences at Clemson University began to question how the department could best train its graduate students for the changing market. One result of this questioning was to begin advising all of the students, even those whose primary interests were in pure mathematics, to take a broader range of courses. In order to include a broader range and still maintain quality, most of the students at the M.S. level began taking more courses than were actually required at that time. The rationale for taking these additional courses was that the graduates would have the option of pursuing nonacademic careers or would be able to teach courses in applied areas. (It was predicted that the *academic* market for mathematical sciences graduates would also be much stronger in applied areas.)

At about the same time, the mathematics faculty of Washington State University also began to move deliberately toward meeting the challenge of the situation. A relatively early symptom of the shift was the decision, in 1971, to adopt the name "Department of Pure and Applied Mathematics." Active interest in applications was used as an important criterion in the selection of new faculty members, and this led to the introduction of new courses oriented toward applications, more doctoral theses of an applied character, and other effects contributing to a major new emphasis on applied mathematics in the department.

When the National Science Foundation (NSF) began making funds available for grants to explore alternatives in higher education, both departments realized that such a grant would provide the opportunity to expand their existing ideas and experiment with new ideas for significantly different graduate programs.

In 1974, WSU and Clemson cooperated in requesting from the NSF financial support for intensive development of new graduate curricula aimed at preparing students for nonacademic careers. The preparation of the NSF grant proposals required approximately a year. This preparation included numerous discussions with industrial representatives and educators from other institutions as well as extended consideration within the two faculties themselves. The main concerns were, first, the goals of such a program and, second, the best methods to

*See R. E. Gaskell and M. S. Klamkin, "The Industrial Mathematician views his profession: A report of the Committee on Corporate Members." *American Mathematical Monthly*, *81*, 699-716 (1974).

achieve those goals. In the summer of 1975, grants were awarded to both institutions.

Two paragraphs from WSU's proposal to NSF may adequately convey the purposes of these projects and the spirit in which they were conceived:

"The goal of the project described in this proposal is to develop at Washington State University, over a three-year period, a program alternative to present academic programs in mathematics which will produce graduates . . . who are mathematical scientists with the background and perspective needed for productive collaboration with nonmathematicians in dealing with problems amenable to mathematical approaches.

"We should perhaps emphasize that we are not aiming at programs of vocational training in the narrow sense. It would probably be impossible, and in any case it would surely be short-sighted, to tailor any program of graduate education to a detailed set of specifications reflecting present-day job descriptions. Our ultimate objective is at the same time more modest and ambitious: to produce a new breed of mathematicians who, on the basis of carefully planned programs of study and apprenticeship, will be able immediately to interact productively with the 'real world,' but will be able also to grow and adapt themselves to the profound and accelerating changes that surely lie ahead."

At Clemson, during the first three months of the grant, the first draft of an actual curriculum was developed. In the fall of 1975 this draft was presented at a conference at Washington State University which was attended by representatives from both industry and academia. Also in the fall, this draft was examined in detail at a two-day conference for the grant's board of advisors. [See Appendix B to Part II.] Valuable input for the program was derived from both of these conferences and from discussions with other professionals during that period. In December, the final program was formally approved by the Clemson faculty and graduate school.

The timetable at Washington State University was less rapid, but by the end of the first year new curricula had been defined, and needed courses had been developed; expert visitors had contributed many valuable ideas; and in the field, the project Coordinating Committee had consulted numerous mathematicians and personnel officers responsible for recruiting mathematicians. The first graduate students specifically identified with the new program at Washington State University were admitted in the fall of 1976.

Throughout the preparation and the implementation of the proposals, there was substantial interchange of ideas between

Clemson and Washington State. In addition to written and telephone correspondence, there were eleven visits by Clemson personnel to Washington State and ten visits by Washington State personnel to Clemson. Also, a pair of professors exchanged positions for the year 1976-1977. The development of several courses at each institution was particularly aided by these cooperative efforts.

The two traditional graduate degrees are, of course, the master's degree and the Ph.D. Our recent experience, underscored by the testimony of many of our advisers, makes it clear that there is a steadily increasing demand among both graduate students and employers for the level of training represented by the master's degree. Whatever its purpose and status may have been in the past, this degree may be emerging as the leading professional degree in mathematical science. Indeed, there already appear to be many more professional opportunities for holders of a master's degree than for Ph.D.'s—or B.S.'s and B.A.'s—in mathematics.

While not forsaking our commitment to the doctorate, we have therefore given a good deal of thought to developing meaningful curricula at the M.S. level. They do not provide the specialized depth and research skills expected of a good doctorate, but they do, we think, offer a fine background for work at the "general practitioner" level, with some opportunity for special concentration. They also, with minor modifications, serve as the initial phases of doctoral programs.

The Ph.D. degree, historically, certifies that the recipient has demonstrated an ability to do original research meeting prevailing standards, and thereby to contribute to the sum of human knowledge. The Ph.D. holder is expected to have a good general grasp of the core material in the field and to be a proficient and productive scholar in some special area.

Mathematicians with the doctorate who work in nonacademic positions are not always expected to do research, and are sometimes actively discouraged from doing so. "Research productivity" is simply often not the scale by which their professional value is measured. Instead, what is usually required is general problem-solving ability: the knack of bringing one's mathematical, general analytical, and other skills and knowledge successfully to bear on problems whose solution is of some importance to the organization. For a person who hopes to meet these expectations, such things as nonmathematical knowledge, communication skills, computer literacy, and a good sense for when it's time to stop working on a problem rank in importance with mathematical proficiency in the strict sense.

These observations have certain implications for the educa-

tional problem. If the graduate education of a prospective non-academic mathematician is to be meaningful, it must be liberated to some extent from the traditional conception. More emphasis must be put on development of the useful characteristics just mentioned. This is precisely the goal of the Clemson and Washington State programs.

Under the two grants, a total of four major meetings and several smaller ones have been held at one or the other of the two universities. These meetings were attended by active participants in both projects, representatives of government and industry, and representatives of other universities where related projects were under way or being considered. The purposes of the meetings included evaluation of the Clemson and Washington State programs and, more generally, a sharing of ideas and experiences related to the whole problem of graduate education in the applied mathematical sciences. (Proceedings of several of these meetings are available.)

One of the meetings, and the largest, was held at Clemson, August 26-27, 1977, under the title "Graduate Programs in the Applied Mathematical Sciences: Perspectives and Prospects." Approximately one third of the program was devoted to the subject of including meaningful models, projects, and applications in the graduate curriculum. The consensus of the participants was: although ideally, appropriate applications should be presented in each course of the curriculum, in practice, crowded course schedules usually short-change significant discussions of applications; models/projects courses, however, help to remove this deficiency, offering a problem orientation instead of a subject discipline orientation. One participant offered a statement of the goals of the internship/project course/models course experience which may be summarized as follows:

1. To acquire skills in problem identification, communication, integrating multiple methodologies, and dealing with coworkers in the presence of fuzziness.
2. To develop a motivation, a questioning attitude, and an understanding of limitations of data, tools, and the institutional framework within which problems must be solved.
3. To learn to appreciate one's own qualifications and their limits, and to know where and how to get help when it is needed.

This list goes far to describe how the spirit of the new programs at Clemson and Washington State differs from that of the more standard and traditional programs.

Details of the two projects are given in Parts II (Clemson)

and III (WSU) of this report. The report concludes with a bibliography of items relevent to the whole subject of graduate education in applied mathematics.

It is hoped that this report, besides informing prospective graduate students who may be interested in one or the other of the two programs, will provide food for thought for mathematical faculties in other schools where similar reforms have been undertaken or are being considered.

PART II. CLEMSON UNIVERSITY PROJECT

At Clemson University the first phase of the grant implementation was the development of the M.S. program. The program, approved in December, 1975, was the result of many hours of discussion among the Clemson faculty and of input from the board of advisors for the grant project, representatives from Washington State University, and other professionals from both academia and industry. The development of this program was based on the following premises:

1. The major source of employment for mathematical scientists in the future will be nonacademic agencies.
2. Most such employers will require more than a B.S. degree but less than a Ph.D. degree in the mathematical sciences.
3. Employers will prefer personnel who possess not only a concentration in a particular area of the mathematical sciences, but also diversified training in most of the other areas.
4. Graduates should have had more than superficial education in applying mathematical techniques to solve problems in areas other than the mathematical sciences. Inherent in such training is the ability to communicate, both orally and in writing, with persons from these application areas.
5. It is desirable to obtain such broad-based education in the mathematical sciences prior to specializing for the Ph.D. degree.

As a result of premise 3, all students are required to have a minimal competency in each of the areas: computing science, core mathematics, operations research, and probability and statistics. Thus, all students are required to earn (or to have earned prior to entry into the program) credit in the following courses:

(1) Computing science: An undergraduate course in a high-level programming language, a numerical computing science course, a computing course emphasizing discrete models.

(2) Core: One undergraduate course in each of linear algebra, abstract algebra, and advanced calculus, two core courses beyond advanced calculus and modern algebra.

(3) Operations research: One course in deterministic optimization.

(4) Probability and statistics: A course in basic statistics, a senior-level course in probability, an advanced course in applied statistics, and an additional course in statistics or operations research.

As a result of premise 4, all students are required to take a models course. The models courses are taught by someone in the application area or are team-taught and are designed specifically for students in the mathematical sciences. Several models courses have already been developed: one in biomathematics, one in environmental engineering, and one in management science (production and inventory control).

In order to attain sufficient depth in a concentration area, each student is required to take six additional courses to be selected from or to complement the concentration areas.

Every student is also required to complete a project (either in connection with some course or independently) and to present the result of the project to his/her committee.

The following is a sample program for a typical student entering the M.S. program at Clemson University. Most students will take two academic years and a summer to complete the program.

SAMPLE M.S. PROGRAM

	Semester hours
Digital Models	3
Numerical Processes	3
Core	6
Applied Models	3
Mathematical Programming	3
Data Analysis	3
Operations Research or Statistics	3
Concentration Area (including electives)	18
Project	
TOTAL	42

The concentration areas are:

Algebra
Analysis
Probability and Statistics
Operations Research
Computing Science

The formal M.S. degree requirements and sample programs are presented in Appendix A.

The next phase in the implementation of the grant proposal was the revision of some existing courses and the development of some existing courses and the development of some new courses. Excluding the models project courses, which will be discussed separately, the following courses were either new courses in the curriculum or ones which had been considerably revised:

Applied Algebra
Combinatorial Mathematics
Calculus of Variations
Dynamical Systems Theory
Fourier Series
Mathematical Analysis I and II
Applied Functional Analysis I and II
Digital Models
Simulation Theory
Numerical Processing
Data Structures
Systems and Software
Network Flow and Integer Programming
Stochastic Methods in Operations Research I and II
Applied Multivariate Analysis
Data Analysis
Applied Time Series Analysis
Project Course

See Appendix D for course descriptions.

Numerous visitors [See Appendix B] provided much assistance in the development of the above-listed courses and the models courses to be discussed in the next section.

The development and testing of an innovative Ph.D. program was also a portion of the grant proposal. Under the proposed program the Ph.D. candidate would follow approximately the same curriculum as a Master's candidate for the first two years. During the latter portion of the program the student would specialize in one of the mathematical sciences areas.

For the student choosing to specialize in an area of core mathematics, the latter portion of the program would closely resemble the traditional Ph.D. program with the following important differences:

(1) the education up to the point of specialization would be broader and thus provide a better basis on which to choose a specialty area;

(2) if the student planned to pursue an academic career, the earlier phase of the program would provide better cre-

dentials than the traditional degree, especially at institutions not offering the Ph.D. degree (where there is presently the greatest demand);

(3) if the student decided (or was forced to decide) to pursue a nonacademic career, the program would provide a significantly better basis for this choice than that of the traditional Ph.D. program.

An innovative aspect of the Ph.D. level portion of the grant activity was experimentation with a program which would combine a student's interest in an outside area with the appropriate areas of mathematical sciences.

Two students wrote their dissertations in simulation theory basing much of their work on a railroad traffic problem for which real data were available. The efficiency (time) of the computer program associated with one of these dissertations effected a startling improvement in existing program concepts. This work illustrates for the Clemson Department of Mathematical Sciences a change (in the direction of problem orientation) from the customary type of dissertation. Incidently, the students' extensive knowledge of abstract algebra was an important factor in the development of their dissertations. One student combined analysis with electrical engineering and has submitted part of his dissertation to an electrical engineering journal. Another student majoring in analysis did research in modeling ecological systems which utilized his background in analysis, numerical analysis, and statistics. One student whose research area was abstract algebra, but who also had extensive training in computer science, was hired by a large industrial firm specifically because of his combination of abstract algebra with computer science. Seven recent Ph.D. recipients left Clemson for the following career opportunities:

J. A. Bate	J. P. Stevens
H. E. Hodges	Milliken & Company
H. Kaneko	Louisiana Polytechnic Institute
D. H. Lubbers	Mount Union College
M. A. Matar	Bell Laboratories
G. T. Mertens	TRW Company
T. S. Tosch	postdoctoral work in biostatistics (University of Washington)

Several other students have been directed by faculty within the Mathematical Sciences Department to Ph.D. degrees within the Management Science Program, and all were eagerly sought by academic and nonacademic employers. The Management Science Program is an interdisciplinary program which is jointly

administered by the Department of Industrial Management and the Department of Mathematical Sciences.

The activities with respect to the Ph.D. program, which occurred during the project period, culminated in the approval by the faculty in spring, 1979, of the following Ph.D. requirements:

1. All students completing the Ph.D. program are expected to have obtained breadth in the mathematical sciences similar to that of Clemson's M.S. program.

2. The student must complete at least 3 or 4 advanced courses outside the area of specialization.

3. The formal course offering will not be vertical as in the past. Thus, to insure depth in some areas, the student should begin no later than the third year to participate in formal seminars and pursue independent research.

4. The Ph.D. qualifying exam will be in two parts:
   (a) Part one of the exam will consist of 3 written exams with at most one from each of the areas: Algebra, Analysis, Computing Science, Operations Research, Probability and Statistics.
   (b) Part two will be a written examination administered by the student's advisory committee, will emphasize the student's major area, and will be taken within a year of the student's passing the examinations in part one.

MODELS AND PROJECT COURSES

The requirement that all students be required to take a models course is a major feature of the M.S. program. The principal goal of the models course is to present a preview of the experiences which confront mathematicians who are consulted for help in the mathematical formulations and solutions of problems from such diverse areas as biology, environmental engineering, and management, to name a few. Three models courses were designed and offered as specified in the grant proposal. Another models course was offered by Professor Jerome Spanier of the Claremont Graduate School (Professor Spanier was a grant-sponsored visiting professor for the 1978 spring semester). Some of the students satisfied their modeling requirements by taking regularly scheduled courses in other departments. Such courses were carefully screened to ensure that prerequisite training in "outside" terminology and concepts was not excessive and that the emphasis was on initial problem formulation and subsequent refinements rather than elementary mathemat-

ical concepts. Also available to the student are a two-semester course sequence in stochastic models in operations research and a two-semester course sequence in digital models.

Descriptions of four of the models courses follow:

Production Scheduling and Inventory Control—This course is a two-semester course developed for second-year graduate students. One of the primary objectives of the course is to expose the students to some of the work that has been done and is currently being done by practitioners utilizing the type of mathematics to which the students have already been exposed in their previous course work. The areas of inventory control and production scheduling have long histories of attempts at modeling for the decision maker and therefore provide a fertile field for different mathematical models including linear programming, dynamic programming, goal programming, quadratic programming, and various stochastic models.

The course is introduced by providing the students with a number of complex, realistic inventory and production scheduling problems in case formats. At specified points in the course the students, working in teams of two or three, are called on to make managerial reports as to their recommendations concerning the problems.

For several weeks the instructor lectures on "classical" inventory and production scheduling models. Additionally, each team of students chooses two recent developments in the field of inventory and production scheduling models, makes a presentation to the class on these models and develops a project for the other class members to insure their understanding of the presentation. Thus, when the teams finally approach their semester case, they have been exposed to much of the classical as well as the more recent literature. Then, each team must select from this wide array of models the one approach or combination of approaches it feels is most suitable for its particular case, develop solutions, and defend them before peers.

Throughout the course, particular emphasis is placed on the explicit and the implicit economic assumptions inherent in models and their implications. The student is taught to search for these assumptions and to evaluate their impact on the usefulness of results. Additionally, since most of the models employ cost estimates, a great deal of time is spent discussing the conversion of accounting data into the necessary data for modeling.

During the second semester of the course, the students, under the direction of the professor, work with a large company in the area. At a series of meetings, the top management of the company introduces the students to the general nature of the business and the organizational structure of the company. They

interview various managers, secretaries, and technicians from different functional areas that are concerned with inventory control, e.g., production, shipping and receiving, purchasing, accounting, etc. This part of the project culminates in a comprehensive flowchart approved by the firm and a written report describing and analyzing the system both as to its strengths and weaknesses.

As the students are working on the flowchart for the system, they are encouraged to look for any specific problems that they might encounter which could be approached by the techniques discussed during the first semester. After the initial phase of the study is completed, the students are divided into teams and each team is required to make three proposals as to a project on which it would work for the rest of the semester. From the proposals made, the professor, with the advice of the firm's management, selects one of the proposed problem areas for each team. Each team then specifically defines the problem, gathers the necessary data, and finally makes recommendations to the firm as to how to solve the problem.

The final reports are presented to the management of the firm and a group of professors both in written and oral form. Both of these groups critique the reports and question the students as to the assumptions, estimates, etc.

Professor E. E. Burch of the Industrial Management Department at Clemson University developed the appropriate course material for this course during the summer of 1975 and subsequently offered the two-semester course during the academic years 1975-1976, 1976-1977 and 1978-1979. His description of the course philosophy and content is contained in (1) and (2). Student enthusiasm for this models course was unusually high, and several students reported that the clinic experience given in the second semester was a positive factor in subsequent job interviews. The industries were also enthusiastic concerning the benefits received from the student projects.

Two professors observing the Clemson project with partial support from the N.S.F. grant (Professor Woodworth of Drake University and Professor Smith of Appalachian State University) were active auditors of this course and gave positive impressions of its value in a student's program.

Mathematical Modeling in Biophysics and Quantitative Biology—The objective of this course is to provide some general principles in the biological sciences, to acquaint the student with some modern aspects of the biological sciences in which mathematical methods have proven to be of use, and to bring the student to a level where it is possible to participate in a student project in the biological sciences.

Since the students will already possess more mathematical preparation than is typical for most science majors, the course emphasizes the assumptions of the mathematical models studied and the interpretations which can be given to the solutions of these models. This approach thus differs from that used in Physics 617 and Physics 618, which are courses with similar objectives but with less mathematical prerequisites and more science requirements.

The beginning of the course furnishes necessary additional background in areas including physical chemistry and molecular biology. Following this foundations phase of the course, the major units of study will concentrate on some typical mathematical models which have been important in the biological sciences including general population growth, population genetics, cell kinetics, radiation biophysics, and enzyme kinetics.

Professor B. V. Bronk of the Physics and Microbiology Departments at Clemson developed the course material and offered a one-semester course in 1976. His description of the course philosophy and outline is contained in (2).

Water Resources Systems—The following course description covers a two-semester sequence which is intended for Master's degree level students in the mathematical sciences who have had the courses: Linear Algebra, Advanced Calculus, Theory of Probability, Data Analysis, Introduction to Stochastic Processes, Linear Programming, and a course using the digital computer.

The objective of the course is to provide some general principles in environmental and water resources systems, to study some problems in these systems in which mathematical methods have been proven of use, and to consider in some depth a specific major environmental or water resources problem.

Since the students already have the mathematical tools with which to begin the study of these problems, the major emphasis is placed on the nature of the environmental and water resource systems, the mathematical modeling of such systems, and the interpretations of resulting solutions. In contrast, the course WRE 876 has much the same objective. However, more time is required in that course for the development of the necessary mathematical tools.

The course considers a broad view of the water resources area. Particular emphasis is given to the application of current operations research and systems engineering techniques in the analysis, evaluation, design, operation and management of water resource systems. Among the types of systems considered are water quality, hydrologic and integrated multipurpose systems including reservoirs, regional environmental control systems, power-generating facilities, and industrial water supply

and pollution-abatement systems. Included in each semester is a student project. Guest lecturers from state, federal, and industrial agencies are used to give up-to-date field conditions and constraints for these systems. The product of the second semester is to be a detailed report suitable for submission to an agency or industry dealing with the system(s) studied in the course of the semester.

Topics include:

- Objectives of water resources developments
- Modeling and the systems approach
- Economic efficiency, tangible and intangible factors
- Sources of data for model building
- Water resources system activities in government and industry
- Specific examples of math models in water resources systems, limitations of model, interpretation of results, discussion
- Presentation of class project

Professor B. C. Dysart of the Environmental Systems Department at Clemson University developed the course material and offered a one-semester version of the above course in 1977. The latter one third of the course consisted of competitive team projects using different solution techniques on the same application area. A description of the course philosophy and content is presented in (2).

Mathematical Modeling and Simulation—This course, geared to first- and second-year graduate students, was aimed at the construction, analysis, and interpretation of mathematical models capable of yielding information about significant scientific problems. Attention was focused on the modeling process itself rather than on the detailed solution of equations representing the model. The physical process of diffusion was used to provide the basis for a wide variety of mathematical models.

Both deterministic and statistical techniques were discussed including integral transform methods and fractional calculus, Monte Carlo methods, numerical analytical methods, elementary perturbation analysis, and dimensional analysis and scaling. Applications areas discussed included air pollution transport, nuclear reactor theory, electrochemical diffusion, and the agglomeration of amoebae, among others.

Since the course was problem-oriented, rather than technique-oriented, students worked on a modeling project as part of the course requirements. Topics in the textbook, C. C. Lin and L. A. Segel, *Mathematics Applied to Deterministic Problems in Natural Sciences*, Macmillan, 1974, were covered in the

course as well as material developed at the Claremont Graduate School.

This course was offered during the 1978 spring semester by Professor Jerome Spanier of the Claremont Graduate School during his N.S.F-sponsored visit to Clemson. Two Clemson University faculty members (Professors Reneke and Waide) and three visiting professors (Caveny—Southern Mississippi University, Rodine—Northern Illinois University, and Vandervelde—Hope College) observed this course and constructed and presented a demonstration module (four-hour presentation) on a forest succession mathematical model using data from the Coweeta Hydrological Laboratory (facility shared by Clemson and the University of Georgia). Student members of the course were required to write semester projects involving mathematical models. A list of these projects follows:

1. "World Population Models—Where Are We Heading?" Gerald David Ammons
2. "A Traffic Intersection: Model Evaluation and Simulation," Dale A. Walsh
3. "A Queuing Model for a Single-Server Drive-in Banking Facility," Ann L. Hart
4. "Natural Displacement of Pollution from the Great Lakes," William H. Richardson
5. "Stochastic Model of the Lynx—Snowshoe Hare Predator-Prey System," Pamela Clark and David Clawson
6. "The Age Distribution of a Population—A Look at Long and Short Term Projects," Regina Caveny
7. "How to Save Money by Making Your House More Energy Efficient," Jo Fletcher and Roland Minton
8. "An Inventory Model of a Shoe Store," Steven T. Kramm
9. "Rocket Lauching Trajectories," William Harrod
10. "Enumeration of Information Digits in Primitive BCH Codes," Diane Alberga

The activities and experiences during the past four years by both faculty and students in the application of mathematical science techniques to problems faced by local and regional firms and agencies have resulted in a Projects Course. A description of this course is contained in Appendix D. Students taking the Projects Course undertake projects more substantial than the minimum required for an M.S. project. Potential projects arise from a variety of sources, usually through a faculty contact. Students meet with the "client" group to determine the nature of the problem and then submit proposals for solutions. Upon

completion of the projects, reports are made to appropriate faculty and client members. The six projects completed during the 1978 and 1979 spring semesters are indicated in Appendix C.

Another source for student projects is a Clemson University internal consulting group (Division of Information Systems Development) which employs several graduate students in the Mathematical Sciences Department. The work of this group has been briefly described by Professor Peck in (1).

During the past four years, at least 24 Master of Science papers have been written as a result of problems generated by agencies outside the Department of Mathematical Sciences (business firms and state and federal agencies). Appendix C is a partial list of M.S. papers written during the N.S.F. grant period which treat applied problems in the mathematical sciences. The list represents about 60 percent of the total number of Master of Science papers. Several successful projects completed for external agencies were not used as M.S. papers.

Because of student response, local career opportunities, and available faculty, the Mathematical Sciences Department will probably continue to offer a models course sequence treating topics in management science (production scheduling, inventory control, etc.). Additional offerings of the Water Resource Systems course will occur often as faculty availability and student interests coincide. Because of the lack of student demand, the models course in biophysics and quantitative biology will be replaced by externally scheduled courses, Introduction to Biophysics (Physics 617-8), and Advanced Ecosystem Analysis (Zoology 815-16).

An attempt will be made to isolate particular courses in classical engineering appropriate for graduate students in the mathematical sciences. The omission of this area in the N.S.F. support period (1975-1979) is due to heavy prerequisite material for most established courses (fluid mechanics, chemical engineering analysis, structural analysis, etc.) and the rather limited demand for such training in the Clemson area.

Student response to the models/projects courses has varied depending upon factors such as: the student's perception of the applicability of the course material to his/her subsequent career, the performance of the individual professors involved, and the amount of background material in the particular area (most of the students terminate after two years, so have limited time for project work). One problem encountered at Clemson was that the models/projects courses were usually scheduled in the latter part of the curriculum when students were interviewing for jobs and experiencing end-of-curriculum pressures. Another

problem was the difficulty of evaluating students' accomplishments in this type of course. The response of both students and faculty was overwhelmingly enthusiastic. Many students reported that the models/projects courses particularly impressed prospective employers.

EVALUATION AND DISSEMINATION

The provision in the grant for the various visiting professors and other professionals is considered one of the most important factors in the success of the project. These visitors provided not only continuous input into the program development and implementation but also the most effective means of dissemination of the philosophy, content, and methods of implementation of the program. The types of visits were varied. Many visitors were on campus for one- or two-day colloquia, five distinguished professionals each spent ten days at Clemson, two spent five days at Clemson, and many spent one or two semesters on campus. Appendix B lists the various visitors and the types of visits. Seven of the individuals who spent the academic years 1976-1977 or 1977-1978 at Clemson have been actively involved in the restructuring of the graduate programs at their respective institutions.

The conference on graduate programs in the applied mathematical sciences at Clemson in September, 1977, also served the dual purposes of providing input into and dissemination of information about the project. Twenty-eight applied mathematicians from industry and government and thirty academic mathematicians participated in this conference. See (1) for a list of the participants.

The official board of advisors [see Appendix B] for the grant have evaluated and furnished valuable advice for the project. The members of this board are distinguished individuals in their professions and, thus, are in positions to greatly enhance dissemination efforts. Robert M. Thrall, chairman of the advisory board, has immeasurably contributed to all facets of the project.

Other methods of disseminating information concerning this project included: the participation by staff members in panel discussions in the 1976, 1978, and 1979 winter meetings of the AMS-MAA and the 1978 national meeting of the ACM; the presentation of a special half-day session prior to the Southeastern Section of the MAA, hosted by Clemson in April, 1978; participation in the MAA-sponsored conference, Prospects in Mathematics Education in the 1980's, and in meetings of the Education Committee of SIAM; the distribution, in response to requests, of reports of the Clemson conference on graduate programs in the mathematical sciences; numerous visits by Clem-

son personnel to other colleges and universities. Additional informational presentations at the winter meeting of AMS-MAA in 1980 have been scheduled.

The graduate students at Clemson during the past four years constituted an invaluable source of input into the philosophy, content, and methods of the project and, in the final analysis, will be the most effective means of dissemination. In addition to students' comments gained through the excellent rapport existing between the faculty and the students, comments were obtained from conferences with the director of graduate studies and each student upon completion of his/her work at Clemson. At these conferences, the students were explicitly asked to evaluate the graduate program. The overwhelming response from the students was a most positive endorsement of the program. Several of the graduates who are now working have reported advantages of the training received at Clemson and have also displayed their interest by offering suggestions for the program.

Seventy-seven students received M.S. degrees in the mathematical sciences at Clemson during the four years of the grant. All of them have obtained employment which utilizes their interests and training.

The following indicates the types of activities which these students entered immediately after graduation:

62%—industrial and governmental positions
25%—Ph.D. programs
9%—high school and college teaching
4%—miscellaneous (military, married, etc.)

Some industrial firms and governmental agencies which have employed these students are:

Bell Laboratories, TRW, Duplex Systems, Inc.,
Goodyear, Monsanto, Hanes Corporation, J. P. Stevens,
Consulting firms (local and national),
IBM, Hughes, Delta Air Lines,
Duke Power Co., Texas Instruments, Sperry Univac.
Naval Surface Weapons Center, Southern Bell.
Pratt and Whitney, Mitre Corporation.
Volunteer State Life Insurance Co.

REFERENCES

(1) A Report on the Clemson N.S.F. Conference "Graduate Programs in the Applied Mathematical Sciences, Perspectives and Prospects," edited by T. G. Proctor, Clemson University, Mathematical Sciences Department, Technical Report #274, February 1978.

(2) "Mathematical Modeling Courses Developed under N.S.F. Grant—An Alternative in Higher Education in the Mathematical Sciences." Clemson University, Mathematical Sciences Department. Technical Report. August 1979.

APPENDIX A

FORMAL DEGREE REQUIREMENTS

Entering students are expected* to have a background that includes courses in linear algebra, differential equations, a computer language, and statistics.

Either prior to or during the program, the general distribution requirements must be met:

Advanced calculus, modern algebra, probability, and a subsequent applied statistics course, mathematical programming, an additional course in statistics or operations research, a numerical computing science course, a computing science course emphasizing discrete models, two core courses beyond advanced calculus and modern algebra, and applied models course.

In addition, six courses (to be approved by the student's advisory committee) will be selected from or to complement one of the following specialty areas: Algebra, Analysis, Computing Science, Operations Research, Probability and Statistics.

Every student is also required to complete a project (either in connection with some course or independently) and to present the result of the project to his/her committee.

A minimum of 36 graduate hours is required.

The following pages present some sample curricula for the various concentration areas.

SAMPLE CURRICULA FOR CONCENTRATION AREAS WITHIN CORE MATHEMATICS

Digital Models
Numerical Processes
Data Analysis
Mathematical Programming
Statistics or O.R.
Applied Models

8 courses in one of the following

MATHEMATICS
Algebra (3)
Advanced Linear Algebra
Algebraic Structures

*A student may remove a deficiency in a lower-level prerequisite by taking the course, passing a special examination on the course, or auditing the course and taking another course in the same area which has the deficient course as a prerequisite.

Combinatorial Mathematics
Analysis (3)
Analysis Foundations (1 or 2 from real analysis; complex analysis, R^n calculus)
Applied Analysis (1 or 2 from dynamical systems, Fourier series, control in dynamical systems, partial differential equations)
Electives (2)[1]

APPLIED ALGEBRA
Advanced Linear Algebra
Algebraic Systems I, II
Combinatorial Math
Applied Algebra
Electives (3)[2]

APPLIED ANALYSIS
2 from Analysis Foundations
2 from Applied Analysis
Advanced Courses (2) from applied mathematics, functional analysis, advanced linear algebra
Electives (2)[3]

SAMPLE CURRICULUM FOR CONCENTRATION AREAS WITHIN COMPUTING SCIENCE

Digital Models
Numerical Processing
Core I
Core II
Data Analysis
Mathematical Programming
Statistics or O.R.
Applied Models
Numerical Analysis I
Simulation Theory
Numerical Analysis II or
Computational Problems in Discrete Structures
3 electives

[1] Students in the core mathematics areas desiring to pursue a Ph.D. program in core mathematics should select the elective courses to strengthen either algebra or analysis. Students terminating with a M.S. degree should select the elective courses to strengthen an application area.

[2] Students wishing to complement the applied algebra program with a strong program in other areas should consider the following choices for the elective courses.
(a) computing science—data structures, computational problems in discrete structures, digital models;
(b) operations research—advanced linear programming, integer and network programming, nonlinear programming;
(c) statistics—linear statistical models (2 courses), applied multivariate analysis.

[3] Suggested elective courses for the applied analysis program include numerical analysis, Engineering College courses in fluid dynamics, elasticity, ets., stochastic processes, advanced statistics.

SAMPLE CURRICULA FOR CONCENTRATION AREAS WITHIN OPERATIONS RESEARCH

Digital Models
Numerical Processes
Core I
Core II
Data Analysis
Stochastic Processes
Applied Models
Mathematical Programming
Advanced Linear Programming
Stochastic Models in O.R. I
Project Course

3 courses in one of the following

MATH PROGRAMMING
Nonlinear Programming
Integer & Network
Elective

STOCHASTIC METHODS
Stochastic Models in O.R. II
Applied Multivariate Analysis
Elective

STATISTICS
Applied Multivariate Analysis
Time Series Analysis
Elective

COMPUTING SCIENCE
Numerical Analysis
Data Structures
Elective

APPLICATION
3 courses in an application area

SAMPLE CURRICULA FOR CONCENTRATION AREAS WITHIN PROBABILITY AND STATISTICS

Digital Models
Numerical Processes
Core I
Core II
Mathematical Programming
Applied Models
Data Analysis
Statistical Theory
Regression/Response Surface
Project Courses

4 courses in one of the following

STATISTICAL METHODOLOGY
Experimental Design
Applied Multivariate Analysis
Time Series Analysis
Elective

STOCHASTIC MODELS
Stochastic Processes
Stochastic Models in O.R. I
Times Series Analysis
Elective

STATISTICAL THEORY
Stochastic Processes
Experimental Design
Applied Multivariate Analysis
Additional Core

STATISTICAL COMPUTING
Information Systems
Applied Multivariate Analysis
Statistical Computation (Proposed)
Data Structures or Monte Carlo Methods

APPENDIX B

MATHEMATICAL SCIENTISTS VISITING CLEMSON IN CONNECTION WITH N.S.F. GRANT

I. Board of Advisors

H. T. Banks	Brown University
J. S. Hunter	Princeton University
R. J. Lundegard	Office of Naval Research
D. S. McArthur	Milliken and Company
J. M. Ortega	N.C. State University and ICASE
R. M. Thrall*	Rice University

*Chairman

II. Participants at Clemson/N.S.F. Conference, "Graduate Programs in the Applied Mathematical Sciences: Perspectives and Prospects"

The twenty-eight nonacademic and thirty academic visiting participants are listed on pages 53-55 in the report of this conference, available as Clemson University Department of Mathematical Sciences, Technical Report #274.

III. Faculty Visiting Clemson Project for Extended Period (1-2 semesters)

D. J. Caveny*	Mississippi Southern University
M. E. Hammett	Furman University
C. T. Long	Washington State University
L. L. Long	Tennessee Technological University
G. L. McGrath	Pittsburgh State University
F. R. McMorris*	Bowling Green University
D. L. Minh	New South Wales Institute of Technology
T. A. Newton	Washington State University
R. J. Plemmons	University of Tennessee
J. T. Poole	Furman University
J. R. Reay*	Western Washington University
H. B. Reiter	University of North Carolina at Charlotte
B. H. P. Rivett	University of Sussex
R. H. Rodine*	Northern Illinois University

S. E. Sims*	Louisiana Technological University
J. R. Smith*	Appalachian State University
J. Spanier*	Claremont Graduate School
C. E. Snygg	Humboldt State University
W. L. Woodworth*	Drake University
R. A. Vandervelde	Hope College

IV. Mathematical Scientists Who Advised Faculty in Special Areas (2 weeks)

D. Klingman	(Network Flow Models and Algorithms) University of Texas
J. B. Kruskal	(Statistics) Bell Telephone Laboratories
M. F. Neuts (one week)	(Queueing Theory) University of Delaware
H. H. Shugart	(Mathematical Models in Ecosystems) Oak Ridge National Laboratory
R. M. Thrall	(Models in Decision Theory) Rice University
R. A. Tapia	(Numerical Techniques in Statistics and Operations Research) Rice University
W. H. Fleming (one week)	(Stochastic Control Theory) Brown University

V. Mathematical Scientists Visiting Clemson Project for Short Periods Other Than for the N.S.F. Conference

J. J. Bowers	Rollins College
D. W. Bushaw	Washington State University
L. Carlitz	Duke University
J. A. Cima, W. W. Smith	University of North Carolina
J. A. Cochran	Virginia Polytechnic Institute
W. M. Cunnea	Washington State University
W. H. Fleming	Brown University
T. G. Hallum	University of Tennessee
G. A. Hewer	Naval Weapons Center, China Lake, CA
D. C. Hoaglin	Harvard University
M. J. Kallaher	Washington State University
M. S. Klamkin	University of Alberta

*Partially supported by N.S.F.

D. Klingman	University of Texas
J. S. Kowalik	Washington State University
D. L. Kreider	Dartmouth College
W. L. Lucas	Cornell University
R. M. McConnel	University of Tennessee
V. K. Murthy	University of Southern California
D. A. Ott	Milliken and Company
B. J. Prochaska	Milliken and Company
R. L. Saunder	Southern Railroad
S. C. Saunders	Washington State University
V. D. Thornbill	The Coca Cola Company
D. H. Wagner	University of North Carolina
W. A. Webb	Washington State University
A. B. Willcox	Mathematical Association of America

APPENDIX C

PARTIAL LIST OF 1976-1979 STUDENT M.S. PROJECTS
(Application Oriented)

5/7/76	
Stephen L. Benz*	Temperature Effects on Zooplankton Population Levels in Lake Keowee (U.S. Wildlife)
Kitty S. Boulware and Carolyn L. Williams*	The Review and Applications of a Quadratic Approximation Model for Determining Production and Employment Scheduling
James E. Carrender*	An Application of the M Salesman Traveling Salesman Problem
Sidney N. Diaz and John F. Rudisill*	Analysis of an Inventory System
Harvey I. Duhon	A Mix Assembler
Karen Nichols	Failure-Rate Analysis Applied to Recidivism
Robert A. Potter	The Pure Credibility Premium and a Linear Approximation
Daniel P. Y. Tsui	The Reliability of Regression Solutions: A Look at Computational Accuracy and Stable Solutions
James R. Vaughan, Jr.	Smooth Curve Plotting Applied to N.A.C.A. Airfoils Using the Zeta Plotter
8/9/76	
Eliza B. Jameson and Tecie C. Thomas*	A Study of Transportation Needs Between Several Health and Social Service Agencies in the City of Greenville
12/16/76	
C. F. Jeff Chen*	A Screen Panel Discussion Pre-Processor
5/6/77	
William L. Bridges	A Command Language Structure for Interactive Statistical Systems
Norma Gail Brownlee and Angela S. Cribb*	A Study of the Greenville County Law Enforcement System Using

	the Rand-Patrol Car Allocation Model
5/6/77	
Margaret J. H. Chang	Control Limit Replacement Based on Cost Criterion Under Markovian Deterioration
Jean L. Hannegan and Wesley M. Stephens*	Application of Sampling Techniques to a Physical Inventory
Karen M. Hetrick and John F. Kirby, Jr.	Eigenanalysis Used For Model Identification for Time Series Data
Thomas E. Kenelly	A Study of the Location of Facilities on a Plane
James E. Scurlock, Jr.*	Design and Implementation of the Scribe Text Processing System
Karen L. Stephens	A Development of Ideal Multiple Choice Items
Della M. Stephenson	A Composite Model of Brand Choice Behavior
8/6/77	
Jacque W. Davison*	The Influence of Scholarships on Enrollment Predictions: A Model
Charles J. Van Blaricom*	Readability Program
5/12/78	
Robert W. Aldred	A Queueing Approach to Determining the Optimal Hourly Utilization of Intake Clerks in the Greenville Public Health Center
Elizabeth T. Higgins	The Jeep Problem
Patricia A. Hutchison*	An Approximation Technique for the Analysis of Multi-Server Queueing Systems
James R. Rieck and Fidelis Ikem*	A Study of the Showrate at Clinics in the Greenville County Health Department
James A. Terell*	An Approximation for the Distribution of the Skein Break Factor of Cotton Yarn
Judy L. Walden*	The Design of a Screen Management System
Elizabeth L. Winey*	Computer Architectures for Data-Flow Computations
8/78	
Pam Clark*	A Nonlinear Parameter Estima-

	tion Problem in the Study of Salt Marsh Production
Jeanne C. Mitchell*	A Stochastic Model of Parasitism of the Mexican Bean Beatle in Soybeans by *Pediobus Foveolatus*
5/11/73	
Michael S. Dennis and Deborah J. Frye*	Analysis of a Finished Goods Inventory Control System
Jan R. Garner*	A Study of Multi-Machine Assignment Techniques Used by Industrial Engineers
Roland B. Minton	Stochastic Computations in Minimum Variance Control Theory
Maria del Carman Vargas*	A Linear Programming Approach to Mill Planning
Dale A. Walsh	An Adaptive Control Problem
Clarence J. Zeringue, Jr.	Interfacing an IBM/370 with a Series/1 Mini

*Generated by organizations outside the Department of Mathematical Sciences.

APPENDIX D

COURSE DESCRIPTIONS

APPLIED ALGEBRA
(New Course)

Objective: To acquaint the student with various algebraic structures as they are applied to other areas in the mathematical sciences, such as digital computation and data communication.

Description: Topics vary with the instructor's background and experience, but are largely confined to the algebraic aspects and applications of the following: Lattice theory, Boolean algebra, switching theory and electronic gating networks; finite-state sequential machines, including reduction, simulation, and electronic realizations; applications of finite group theory to network complexity; Polya-Burnside theory of enumeration, with applications of group actions and semidirect products, algebraic decompositions of finite-state machines, an overview of algebraic coding theory, using as a vehicle the 1969 mariner fly-by of Mars.

COMBINATORIAL MATHEMATICS
(Revised Course)

Objective: To introduce the student to some of the standard techniques used in attacking discrete mathematical problems with particular emphasis on enumerative analysis and graph theory. The major change from previous courses taught under this title has been the inclusion of introductory graph theory, a topic needed by those students going into further courses, such as discrete simulation and flows in networks.

Description: The topics covered in the course include permutations and combinations, generating functions, recurrence relations, inclusion-exclusion, as well as more generalized inversion techniques, Polya's Theory of Counting, and basic topics from graph theory including path problems, trees, circuits, cutsets, dominating sets, independent sets, and chromatic numbers.

CALCULUS OF VARIATIONS
(Revised Course)

Objective: To provide students with some insights into the foundations of optimization and dynamical systems by giving

them an overview of contained optimization and an introduction of optimal control.

Description: Included in the course are a review of certain advanced calculus topics including convex functions, derivatives, and some geometry, an introduction to linear spaces, Gateaux and Frechet differentials, the adjoint theory for continuous linear transformations, and the Inverse Function Theorem, the fundamental theory of the calculus of variations, including a general version of the Lagrange Multiplier Theorem and the Pontryagin Maximum Principle, optimal control taken up via some examples, and introductions to minimum norm problems, minimum time problems, and dynamic programming.

DYNAMICAL SYSTEMS THEORY
(Extensively Revised Course)

Objective: To provide a unified approach to the modeling of dynamical processes and to introduce current techniques in the analysis of such processes. A system theoretic approach is used to achieve the first objective, while methods of linear analysis are used to meet the second.

Description: Methods of linear analysis and algebra and used to analyze general dynamical system properties. Topics studied include block diagrams, signal flow graphs, transfer functions, transition functions, input-output maps, linearization, canonical forms, stability and control. The problems of prediction control and realization of dynamical processes are considered and illustrations of these problems from the fields of engineering, management, economics and the life sciences are studied. Emphasis is placed on deterministic systems and in particular, on those processes which may be realized by ordinary differential equations, difference equations or integral equations. The system properties of linearity, time invariance, causality, memory, observability, controllability and identifiability and their place in the analysis of system problems is studied.

FOURIER ANALYSIS
(Revised Course)

Objective: To provide an understanding of basic concepts of Fourier Analysis by using inner product space geometry. Approximation, optimization, and representation problems are considered and in particular, techniques for the representation and manipulation of continuous and discrete functions are studied. The course provides the statistics student with basic concepts in the analysis of time series and stochastic processes, it provides

the electrical engineering student with mathematical foundations for digital signal processing, and it provides the systems analysis student with basic methods in the analysis of dynamical systems.

Description: The following topics are covered: Inner product spaces, least squares approximations, orthogonal families of functions, Fourier transformation, singular functions, discrete Fourier transforms, the FFT algorithm, convolution, correlation, applications to differential equations.

MATHEMATICAL ANALYSIS I and II

(Revised Course)

Objective: To develop concepts which the student will need in diverse future courses, including nonlinear optimization (topics such as Lagrange multipliers), numerical approximation (topics such as Taylor and Bernstein polynomials), probability (the Jacobian and change of variables), and graduate Real Analysis (introductory Lebesgue measure). A shift of emphasis toward the R^n geometry and away from the more abstract metric space setting is needed to meet these objectives. Riemann-Stieltjes integration is replaced by Riemann integration, while the coverage of differentiation (inverse and implicit function theorems) is considerablev broadened through the availability of more time.

Descriptions Included in the course are topological concepts in Euclidean n-space, continuous functions, uniform convergence, differentiable mappings, inverse and implicit function theorems, constrained extrema and Lagrange Multipliers, integration in R^n, Fubini's Theorem, change of variables.

APPLIED FUNCTIONAL ANALYSIS I and II

(Extensively Revised Course)

Objective: To introduce students to the theory and application of linear analysis. Topics related to differential equations, control systems, approximation and optimization are considered. The course is designed to provide a foundation for the mathematical analysis of models occurring in engineering, operations research and other sciences.

Description: The structure of normed linear spaces and inner product spaces together with linear operators and functionals is considered. Topics covered include the solution of abstract equations, approximation, and optimization.

DIGITAL MODELS
(Extensively Revised Course)

Objective: To study the mathematical and computational structure of problem solving by means of a spectrum of problem types. Emphasis is placed on programming practice and modularity. An introduction to the Clemson computing system is provided.

Description: Advanced elements of FORTRAN and WATFIV, elementary primitives, generalized cut-and-try, primitive optimization, modularity and program structure, TSO, use of catalogued procedures, deterministic models with stochastic data.

SIMULATION THEORY
(New Course)

Objective: The study of mathematical and programming models for language independent discrete, continuous and hybrid simulations.

Description: Definitions and structural models of simulations. Automata with operations on data structure; Cartesian products of subsystems. Operator equations with elementary search solutions; problems in several dimensions. Examples selected from a variety of discrete and continuous systems.

NUMERICAL PROCESSING
(New Course)

Objective: To provide an introduction to three important areas of numerical processing; namely the solution of linear algebraic systems, the numerical solution of ordinary differential equations and discrete event digital simulation. Recurrent themes include (1) considerations which distinguish between algorithms for the areas listed above such as storage and computational complexity and (2) experience with at least one professional code for important problems in each of these areas.

Description: Linear algebraic systems topics include solution of triangular systems and Gaussian elimination, LDU decomposition, error analysis and ill-conditioning, computational implementation of LU decomposition in a paging environment, and interactive techniques. Ordinary differential equation topics include Euler's method, the Taylor algorithm and the Runge-Kutta schemes, error analysis, practical Runge-Kutta and step-size selection strategy, a look at variable order Adams and predictor-corrector methods, two point boundary value problems, shooting, and parallel shooting. Simulation topics include sys-

tems, models and system simulation, queueing models, computational model considerations including data structures, time flow, randomness, data handling, initialization and termination, programming language considerations, computational implementation.

DATA STRUCTURES
(New Course)

Objective: The mathematical and computational study of data structure problems as operations on finite families of digraphs. Emphasis is placed on the conflict of sequential storage and the complexity of data in discrete modeling and in the time-space relation.

Description: Problems in array storage; permutation vectors, linked lists; sequential set with I/Ø; storage techniques for digraphs. Elementary applications include elements of data processing and various card games and puzzles. Advanced applications are selected from: polynomials in several variables; extended integer and rational arithmetic; sparse matrices.

SYSTEMS AND SOFTWARE
(New Course)

Objective: This course is designed to develop skills in a student with minimal computer programming background so that he can effectively use a large scale computational facility. Principles of machine architecture, assembler language programming, data management, job control, and software subsystems are described in sufficient detail to provide the student with insight and enable him to investigate and master new computer systems or changes in existing systems with little difficulty.

Description: Machine organization, Operating Systems Overview, Program Support Facilities, Job Management Facilities, Data Management, Library Management and Interactive Systems.

NETWORK FLOWS AND INTEGER PROGRAMMING
(New Course)

Objective: To introduce the student to integer and network optimization models, to emphasize the applications of these models in decision problems and to present the standard algorithms for their solution. Also emphasized are applications of the models to other areas in the mathematical sciences such as combinatorics, graph theory, computer science, and computational complexity.

Description: The course contains a treatment of integer programming models and optimization problems with network structure. Topics include: Max flow-min cut theorem and combinatorial applications, minimum cost flow problems and algorithms (transportation, shortest path, transhipment, out-of-kilter). The relationship between network and integer problems, integer solution methods (branch and bound, cutting plane methods, etc.), special structured problems.

NONLINEAR PROGRAMMING
(Extensively Revised Course)

Objective: To provide an indepth survey of nonlinear programming including applications, theory and algorithms together with their computational implementation.

Description: Fundamental theory of unconstrained and linearly constrained extrema, classical and modern approaches to unconstrained optimization including the conjugate gradient, second derivative and quasi-Newton methods. Modern computational implementations of selected algorithms. Extensions to problems with linear and nonlinear constraints. Large scale optimization. Selected applications, for example a large scale hydroelectric management problem. Potential research topics are discussed as appropriate.

STOCHASTIC METHODS IN OPERATIONS RESEARCH I and II
(Revised Course)

Objective: To introduce the student to both the theory and the application of basic stochastic models frequently arising in Operations Research. The aim of the course is threefold: To provide an introduction to the basic methodology in the development of stochastic models; to present applications of these models and indicate adjustments required for particular situations; and to explore some of the computational issues arising in the applications. Applications are presented as case studies from the literature. The basic objective is to provide the student with the basic knowledge required to formulate models for problems of a stochastic nature, analyze those models, and present recommendations based on that analysis.

Description: The basic theoretical development includes a review of Markov processes and detailed treatments of renewal theory, Markov decision processes and queueing theory. Additional topics are chosen from inventory theory, digital simulation, reliability, and continuous-time models. Each topic typi-

cally includes basic development, computational issues, and applications which may include case studies.

APPLIED MULTIVARIATE ANALYSIS
(New Course)

Objective: To provide an introduction to the theory and methodology of multivariate statistical analysis in a way that students who complete the course successfully will have a good grasp on the proper application of the multivariate techniques, as well as the common pitfalls to avoid. The course places much emphasis upon the underlying asumptions of each model, the empirical validation of such assumptions, the theoretical and practical implications of the assumptions, and the actual applications of the methodology to real data.

Description: The topics treated in this course include: The interface of theory and practice, graphic display of multivariate data, multidimensional scaling, theory of multivariate distributions, univariate and multivariate tests of equality of means, covariances, and equality of distributions, multivariate regression and its relation to univariate multiple regression, ANOVA, MANOVA, and multiple comparison problems, principal components analysis and its relation to factor analysis, analytic rotations in factor analysis, and canonical correlations. Generally, each topic is introduced by a lecture and class notes, followed by numerical problems chosen to be sufficiently small to be suitable for hand computations, then followed by moderately sized real data to be analyzed by employing programs in various statistical packages such as BMDP, IDA, and SAS.

DATA ANALYSIS
(New Course)

Objective: To bridge the gap between theory and practice of statistical data analysis. Some recurrent themes are: The examination of data and graphic displays, the differentiation between statistical significance and practical significance, the use of real data to teach statistical theory and its applications. Also, some aspects of standard statistical theory are taught from not so conventional points of view. Students completing the course successfully will have had much first hand experience in the analysis of real data, including the handling of practical problems associated with data gathering, screening, and editing before a statistical analysis, as well as carrying out enlightened analyses and reporting the results of the analyses in verbal and practical terms understandable by a nonstatistician while sup-

porting technical portions of the analyses must be statistically and mathematically sound.

Description: Topics include methodology in the analysis of univariate statistical data, with emphasis on exploratory analysis and model building, computer plots, transformations, multiple and stepwise regression and criteria for selecting variables, analysis of residuals, model building in time series and ANOVA problems, error analysis by jackknife and random subsampling methods, cluster analysis. The availability of the interactive computer package IDA enables the students to practice the art of exploratory data analysis with ease.

APPLIED TIME SERIES ANALYSIS
(New Course)

Objective: To provide the theoretical framework for understanding the behavior of discrete parameter time series and to apply the theory in developing operational methodology for modeling, estimation and forecasting using real data.

Description: The theoretical aspects of a broad class of models, the so-named ARIMA family of Box and Jenkins, for time series are studied. Every model in the family possesses a unique set of theoretical "fingerprints." Model identification can be viewed as the art of matching the sample fingerprints (smudged by random noise) of an observed time series with a member of the set of theoretical fingerprints. Students learn this art by understanding the implications of the theory and practicing with simulated and actual times series data. This is facilitated by the use of an interactive computer program developed at Clemson called TSA, which contains a unique training module in addition to standard graphical, estimation, and forecasting features. Besides many classroom exercises assigned in common, students present individual projects for classroom critique.

PROJECT COURSE
(New Course)

Objective: To provide an opportunity for the application of mathematical skills to real problems that arise in a practical situation resulting from a client's need.

Description: The department solicits the participation of sponsoring agencies or clients, such as regional industries and governmental agencies. Sponsors and clients suggest topics corresponding to their interests and needs, and from these student projects are identified and assigned to groups of students. Stu-

dent work involves: problem specification, proposed solutions, interaction with client personnel, formulation of models, collection and analysis of data, researching literature, developing computer programs, writing a report and giving oral reports to the client.

PART III. WASHINGTON STATE UNIVERSITY PROJECT

This part of the report consists of three major sections: a general description of the applied mathematics program at Washington State University as it now (fall 1979) stands, largely as a result of the Service-Oriented Options Project; a survey of the activities performed under this project; and several appendices containing further details about aspects of the university, department, and program.

[It should be emphasized that Washington State University offers other graduate programs in mathematics besides those mentioned here. Both masters and Ph.D. programs of a more conventional kind are available, with concentrations in algebra, number theory, geometry, topology, analysis, and statistics. The department also offers the Doctors of Arts in Mathematics, a degree designed to prepare high-quality mathematics instructors for undergraduate institutions. (Further information about these programs may be obtained from the Department.)]

Of course, although the Service-Oriented Options Project has terminated, further additions and changes will be made in the applied mathematics program. The Department of Pure and Applied Mathematics of Washington State University has a long-term commitment to this program, which will surely continue to develop and evolve on the basis of experience and in response to demands and opportunities.

Nevertheless, the descriptions that follow describe an *existing program*. For anyone now contemplating graduate study of mathematics, the program is an unusual opportunity to obtain a sound contemporary background for a useful and satisfying lifelong professional involvement with mathematics.

THE PROGRAM

The increasing emphasis on applications in the Washington State University Department of Pure and Applied Mathematics dates back at least ten years. But the first curricular changes under the Service-Oriented Options Project were made in 1975-1976, and the first students specifically identified with the new program were admitted in the fall of 1976. Of course, some students who had already begun graduate study at Washington State University availed themselves of the new program. One way or the other, approximately fifty graduate students have

entered the new applied mathematics program in 1976-1979.

There has not been much time for students to graduate from the new program, but all who have obtained master's degrees in the program and are not continuing their graduate study have found attractive and appropriate employment. Employers include: Boeing Computer Services (Richland and Seattle, Washington); Texas Instrument Company (Dallas, Texas); Weyerhaeuser Company (Federal Way, Washington); Timberline, Inc. (Beaverton, Oregon). Recipients of recent Ph.D.'s in applied mathematics have taken academic appointments (e.g., Old Dominion University, Worcester Polytechnic Institute).

The new program differs from conventional graduate programs in mathematics in the following major respects:

1. Fundamental "core" graduate mathematics has been reorganized into an integrated sequence of courses.
2. New courses emphasizing interdisciplinary problems, modeling, and computational implementation have been introduced.
3. Students are encouraged to take suitable courses outside mathematics, in departments ranging from Agricultural Economics to Zoology.
4. Curricular recommendations have been collected into four basic programs, called options, which may be adapted to the needs of individual students.
5. Students take internships (and, when possible, "preinternships") as practicing applied mathematicians.
6. Master's projects and doctoral theses are concerned less with the exposition and extension of mathematics itself than with creative applications of mathematics to real-world problems.

THE MASTER'S DEGREE

The master's degree at Washington State University ordinarily requires two years of study for a student with a half-time assistantship. The courses required in all cases (except when they may be waived because of previous study and experience) are:

Math 500 Proseminar
Math 501 Linear Algebra and Analysis
Math 502 Analysis
Math 702 Master's Special Problems

Math 500 (1 credit hour) is required of all graduate students in the department. It deals with basic questions related to teaching mathematics to undergraduates and is normally completed the week before the start of regular fall classes. The great majority of our graduate students are teaching assistants, and

the course was devised to improve their performance in that role; but it is beneficial to others too.

Math 501 and 502 constitute the graduate "core," and are intended to culminate the student's introduction to the mathematics that every holder of a graduate degree in the field should know. Major topics are advanced linear algebra, calculus in n-dimensional spaces, complex analysis and harmonic functions, Lebesgue measure and integration, Fourier analysis, and special functions. (A more detailed syllabus appears in Appendix D.3.)

Math 702 is a university requirement which is interpreted in this program as an opportunity for students of applied mathematics to carry out special projects in the second year. Ideally each project should draw on the student's internship experience(s), if any, and on recent courses and should be a culminating expression, as far as the master's degree is concerned, of the student's skills as an applied mathematician.

Graduate students in applied mathematics are also expected to take:

Math 544 Computational Linear Algebra

This course, which assumes a significant acquaintance with computer programming, acquaints the student with basic numerical approaches to linear algebraic problems.

Courses related more directly to various applications are mentioned below in the descriptions of the options. Other requirements for the master's degree are listed in Appendix A. They concern total credits, residence, and comprehensive examinations.

Master's candidates in applied mathematics are encouraged, with faculty help, to get jobs related to their educational programs for the summer following the first year of graduate work. This kind of position is called a *preinternship*. For various reasons, preinternships are not possible for or desired by all graduate students; but, when possible, they provide a useful exposure to the practice of applied mathematics in an authentic environment. Host organizations for internships arranged so far have included: the Naval Weapons Center (China Lake, California); Battelle-Northwest (Richland, Washington); and Boeing Computer Services (Seattle, Washington).

A student's program should be reasonably cohesive. While a broad general background is desirable, some concentration adds depth and a more productive kind of proficiency. Taking into account the department's and the university's strengths, and drawing on advice and criticism from dozens of expert colleagues both within and outside the university, we have accordingly formulated four basic "options." Each option is a model

graduate program which a student might adapt, in consultation with an advisor, to his or her special needs and aspirations. Washington State University graduate students have also made a significant contribution to the formulation of these options.

The four options are called:
- computational mathematics
- mathematics for natural sciences
- operations research
- applied statistics

We shall now sketch each option: more detail will be found in Appendices A and D.

The option in computational mathematics. The emphasis in this option is on numerical analysis and on the numerical solution of ordinary and partial differential equations, especially as they arise in the natural sciences and technology. Students entering this option should have undergraduate experience in engineering or one or more of the natural sciences and a good background in computer science (FORTRAN or some other scientific programming language is essential; knowledge of data structures, assembler language, other programming languages, and computer graphics is highly desirable).

The following courses are required or recommended in this option.

REQUIRED	
Core sequence (501-502)	10 hours
Proseminar (500)	1
Special Problems (702)	2-4
RECOMMENDED	
Computational Linear Algebra (544)	3
Advanced Numerical Analysis (545)	3
Ordinary Differential Equations (512)	3
Partial Differential Equations (540-541)	6
Mathematical Foundation of Continuum Mechanics (570-571)	6
Electives in Statistics, Computer Science. Engineering	6
Preinternship	
Total	40-42 hours

The option in mathematics for natural sciences. This option emphasizes mathematical methods for dealing with natural phenomena, both physical and biological. Graduates from the option could work with natural scientists in the modeling of a wide range of problems in the sciences, agriculture, and engin-

eering; or, with enough competence in the area of application, might work independently. Good undergraduate background in one or more of the sciences is highly desirable.

(In the early phases of the Service-Oriented Options Project, separate options in mathematics for the physical sciences and mathematics for the biological sciences were contemplated. It was soon discovered, however, that the two lines were converging; mathematical background for work in the natural sciences does not appear to depend very much on whether the emphasis is biological or physical. One option has, therefore, been developed to serve the natural sciences in general.)

The following courses are required or recommended in this option.

REQUIRED	
Core Seqence (501-502)	10 hours
Proseminar (500)	1
Special Problems (702)	2-4
RECOMMENDED	
Computational Linear Alegbra (544)	3
Mathematical Foundations of Continuum Mechanics (570-571)	6
Advanced Numerical Analysis (545)	3
Topics in Mathematical Modeling in the Natural Sciences (586 twice)	6
Applied Probability (Stat 443)	3
Applied Stochastic Processes (Stat 544)	3
Electives, e.g.:	6
Thermodynamics (Chem 533)	
Modeling and Simulation of Ecological Systems (Env S 510)	
Combustion (M E 538)	
Mathematical Physics (Phys 570)	
Modeling of Biological Systems (Zool 554)	
Preinternship	
Total	43-45 hours

The option in operations research. According to the booklet *Careers in Operations Research* published by the Operations Research Society of America, "Operations Research is concerned with scientifically deciding how to best design and operate man-machine systems, usually under conditions requiring the allocation of scarce resources." It draws on a wide variety of mathematical theories (including those of probability, mathematical programming, reliability, queuing, and networks) to deal with a wide variety of problems (energy management, business de-

cisions, transportation, health care, utilities, etc.). There exist separate graduate programs in operations research in a number of universities; the Washington State University program differs from those in its emphasis on the mathematical base. Students entering this option should have some knowledge of computer programming. Background in probability and statistics, optimization, and business or management science (e.g., accounting) is highly desirable.

The following courses are required or recommended for this option.

REQUIRED	
Core Sequence (501-502)	10 hours
Proseminar (500)	1
Special Problems (702)	2-4
RECOMMENDED	
Computational Linear Algebra (544)	3
Operations Research and Game Theory (464)	3
Applied Probability (Stat 443)	3
Data Analysis (Stat 572)	3
Information Structures (Cp S 400)	3
Applied Stochastic Models (BA 542)	3
Introduction to Simulation (417)	3
Topics in Optimization (564)	3
Topics in Mathematical Modeling in Operations Research (586)	3
Preinternship	
Total	40-42 hours

The option in applied statistics. This option is designed to prepare students for careers in applying statistical ideas and techniques to a wide range of areas, including (among many others) actuarial science, agriculture, social and behavioral sciences, biology, engineering, environmental science, forestry, health and medicine, veterinary medicine, technology, quality control, and reliability. Opportunities for well-trained statisticians remain good.

Students entering this option should ideally have studied some probability and statistics as undergraduates, one or more areas of application, and computing.

The following courses are required or recommended for this option.

REQUIRED	
Core (501-502)	10 hours
Proseminar (500)	1
Special Problems (702)	2-4

RECOMMENDED

Computational Linear Algebra (544)	3
Introduction to Probability and Distribution Theory (Stat 429)	3
Statistics for Physical Science (Stat 430)	3
Multivariate Analysis (BA 519)	3
Statistical Theory (Stat 548-549)	6
Data Analysis (Stat 572)	3
Electives, e.g.,	9
Advanced Topics (Ag Ec 512)	
Decision Analysis (BA 444)	
Techniques of Sampling (BA 514)	
Time Series (BA 516)	
Experimental Design (BA 520)	
Applied Stochastic Models (BA 542)	
Research Methodology (BA 566)	
Mathematical Models (Econ 510)	
Econometrics (Econ 511)	
Quantitative Psychology (Psych 513)	
World Population (Soc 430)	
Demography (Soc 530)	
Applied Stochastic Processes (Stat 544)	
Mathematical Statistics and Probability Theory (Stat 560-651)	
Preinternship	
Total	43-45 hours

This option incorporates an earlier "social sciences" option, which was designed primarily to prepare mathematicians for cooperation with specialists in the various social sciences: anthropology, economics, psychology, sociology, etc. (Students interested in work related to economics might also consider the option in operations research.) The use of mathematical methods is expanding very rapidly in these areas, and while the number of mathematicians directly involved in this domain is still relatively small, there are many indications that it is a rapidly expanding field. Suboptions with concentrations in most of the areas mentioned may be devised for individual students by making judicious choice of electives.

THE Ph.D.

The doctorate represents proficiency well beyond the level of the master's degree, at least in one area of specialization. Each candidate for a Ph.D. in applied mathematics at Washington State University is expected to take the most advanced courses available in his or her specialty, pass a "preliminary examina-

tion" on the specialty, have an internship lasting the greater part of a year, and write an acceptable thesis.

The internship may be preceded by a "preinternship" or by on-campus services which might be described as internships, but it is intended that the internship proper should be an off-campus experience of full-time work for 6-12 months in some firm or agency. Besides being paid by the host organizations, interns will receive academic credit (Math 603) for the internship.

In many instances, the internship will raise a problem suitable for treatment in the thesis. In any case, the thesis should describe an original and significant application of mathematical techniques to one or more real-world problems and should be publishable in a reputable research journal (not necessarily a mathematics journal). It is the capstone of the candidate's formal education as an applied mathematician.

The master's degree is not a prerequisite to candidacy for the doctorate, but most doctoral programs will begin very much like master's programs. For this reason, there is no need to describe any options for the doctoral program here. The first two years of the program of a doctoral student will be like one of the master's options. Additional courses will include more advanced courses in the student's area(s) of special mathematical interest, and additional appropriate electives. For example, a student in the natural sciences option might take functional analysis and applied functional analysis (Math 503-504), several seminars in mathematics, and electives in one or more fields of application (e.g., genetics and entomology).

Formal requirements for the Ph.D. are listed in Appendix A.

THE PROJECT

The program described in the preceding pages is the result of much discussion. Participants in these discussions have included not only faculty members and graduate students at Washington State University (both in the Department of Pure and Applied Mathematics and not), but colleagues elsewhere who either visited us or were visited in their offices.

Under its National Science Foundation grant, the Service-Oriented Options project sponsored two "evaluation meetings" in Pullman, one (September 26-28, 1975) near the beginning of the project period and one (June 26-27, 1978) near the end. In both instances, the purpose was to exchange ideas on graduate education for nonacademic careers in mathematics, in particular as they might apply to an institution like Washington State University. Participants represented government agencies, private firms, and educational institutions where there was an

active interest in the problem. (The non-Washington State University persons who participated in these meetings are listed in Appendix B.3.)

A transcript of the first meeting will be sent on request.

Two parallel conferences were held at Clemson University in October 1975 and August 1977. The Service-Oriented Options Coordinating Committee was represented at both.

A large part of the grant provided for visitors on temporary appointment in the mathematics department at Washington State University. The original plan was that there should be three one-year visits, but for several reasons it was decided to bring in more visitors for shorter periods instead.

The intention was that established mathematicians with extensive nonacademic experience could make especially worthwhile contributions to and comments on the developing program if they were at Washington State University long enough to become well acquainted with the overall program and interact directly with faculty and students. We were not disappointed; in a great variety of ways, the visitors under the grant made invaluable contributions to the program. Names of these visitors, with brief notes on their special activities during these visits, appear in Appendix B.1. The visitors participated in the project not only as mentioned, but also by meeting individually with students and faculty; taking active parts in the meetings of the Coordinating Committee; studying and criticizing options of special interest to them; and reporting their impressions to the Project Director and Department Chairman before leaving.

Other visitors to the department, even though visiting us under other auspices (e.g., the project "Mathematics Career Reentry for Women" directed by C. T. Long), have been informed about the SOO project, and their advice has been solicited. An incomplete list of such visitors appears in Appendix B.2.

Also under the provisions of the grant, members of the department have visited private firms and government agencies, mainly in the Pacific Northwest, to describe the project and seek advice about it; to explore possibilities for internships and other forms of interaction; and in general to open new channels of communication with the professional world we expect our graduates to enter. A list of organizations visited in this way appears in Appendix B.4.

The reception in these organizations was consistently cordial and cooperative. While the themes discussed and the viewpoints expressed in the interviews varied widely, the general attitude was one of strong approval for the philosophy of the project. Specific recurrent observations concerned the importance of

being able to: 1. work and, especially, communicate with non-mathematicians (managers, clients, and specialists in other areas); 2. use the computer, at least to the point of knowing how to talk productively with programmers and analysts, and appreciating current software; 3. attack problems in ways that are likely to yield useful results, and stop working on a problem when the results are good enough; 4. pick up new knowledge and skills when they are needed; 5. assume managerial responsibilities when the time comes.

Many events, activities, and involvements of the past few years, besides those already mentioned, have contributed to the development of the Washington State University applied mathematics program.

Many of our colleagues in other Washington State University departments gave generously of their time, knowledge, and creativity to help us formulate the program, especially in the first year. For example, the subcommittees responsible for two of the options were chaired by members of other departments until one went on sabbatical leave and the other moved to another institution. It would be difficult to name all the people, or even all the departments, who made contributions of this kind, but a partial list appears in Appendix B.5. The good ideas they gave us have not yet been exhausted.

The Coordinating Committee has watched related developments at other universities, e.g., Rensselaer Polytechnic Institute, the Claremont Colleges, the University of Arizona, and SUNY at Binghamton. The conferences at Clemson have been very helpful in this respect. In every case, the representatives of those institutions have been generous with information and support. While goals and approaches differ from one school to another, we have learned something from all of them, and hope they can learn something from us.

One useful byproduct of the Project was a survey, sponsored jointly by the Coordinating Committee and the Academic Services Unit (see Appendix F), to identify faculty members in all Washington State University departments who have an active interest in mathematical methods applied to their own fields.

Another activity, which may also be considered to some extent a byproduct of the Service-Oriented Options project, has been the NSF-funded project "Mathematics Career Reentry for Women" (1976-1978). This project, directed by C. T. Long, was designed to provide women who had begun, but not completed, a graduate program in mathematics to return to the field, complete their degrees, and embark on mathematical careers. The Service-Oriented Options program provided an appropriate setting for their studies.

Of course, the development of the options has required the restructuring or reorientation of a number of courses and the introduction of some new ones. These effects have been felt not only in mathematics but also in computer science. Further new courses have been proposed and will probably be established when it appears that they can be staffed. For example, the department intends to establish a graduate seminar in consulting and is considering additional advanced courses in numerical analysis and mathematical programming. There has also been some discussion of possible interdepartmental courses, e.g., a survey of the fundamental ideas of biology for mathematicians.

Our efforts have been publicized at national meetings and in national periodicals, as well as by two interim reports, and, needless to say, by the present report. The response has been one of general interest and approval, and we believe that what we are doing encourages other mathematics faculties to undertake, or persevere in, similar undertakings.

Many faculty members of the Washington State University Department of Pure and Appled Mathematics have made large contributions to the project, and it may be misleading to identify separately the members of the Coordinating Committee However, for the record, the members of this committee have been: Kenneth A. Bergstresser, James A. Cochran, Calvin T. Long, Sam C. Saunders, David J. Wollkind, and Donald W. Bushaw (Chairman).

Finally, credit should be given to our graduate students for the very constructive role they have played in our efforts. The realization on their part that these efforts were for their benefit and for that of their successors does not fully account for the frankness, thoughtfulness, creativity, and generosity with which they have supported the program—nor for the patience with which they have borne some of its growing pains.

APPENDIX A

FORMAL DEGREE REQUIREMENTS

The main formal requirements for the master's and Ph.D. degrees in mathematics at Washington State are listed below. Some more technical requirements (for example those related to time limits for various phases of a program) are omitted for clarity, but can be supplied on request.

1. *The Master's Degree*

Requirements for the master's degree are:

a. Completion, with satisfactory grades, of at least 31 credit hours of approved graduate courses. (Up to eight hours of transfer credit may be given for suitable courses taken elsewhere.)

b. At least one year in residence at Washington State University, and at least one semester of teaching, normally as a teaching assistant.

c. A special project, usually done in the second year. This should be an authentic experience with mathematical modeling, consulting, or research in applied mathematics. (2-4 semester hours of credit are given under Math 702.)

d. Two comprehensive examinations:

i. a written "qualifying examination," in two three-hour parts, covering the material of the "core" courses Math 501-502; and

ii. a final oral examination covering the student's whole program, including certain standard undergraduate material.

A typical master's program (in the natural sciences option) for a student entering the program with no previous graduate work might look like:

FIRST SEMESTER
Linear Algebra and Analysis (501)
Computational Linear Algebra (544)
Mathematical Foundations of Continuum Mechanics I (570)
Proseminar (500)

SECOND SEMESTER
Analysis (502)
Mathematical Foundations of Continuum Mechanics II (571)
Science Elective

SUMMER FOLLOWING SECOND SEMESTER
Preinternship

THIRD SEMESTER
Topics in Mathematical Modeling in Natural Sciences (586)
Applied Probability (Stat 443)
Advanced Numerical Analysis (545)
Science Elective
Qualifying Examination

FOURTH SEMESTER
Topics in Mathematical Modeling in Natural Sciences (586)
Applied Stochastic Processes (Stat 544)
Master's Special Problems (702)
Master's Oral Examination

2. *The Ph.D. degree*

The Ph.D. in Mathematics ordinarily involves two or more years of study beyond the level described above for a master's program. A master's degree, however, is not required.

Requirements for the Ph.D. are:

a. Completion, with satisfactory grades, of at least 72 semester credit hours, at least 34 of which are in graded courses numbered 400 or above. (Transfer credit may be allowed.) Doctoral students in applied mathematics are encouraged to take a significant number of courses outside mathematics, so as to acquire at least a fair familiarity with at least one other field.

b. At least two years of residence, including two consecutive semesters, as a regularly enrolled graduate student at Washington State University.

c. The written "qualifying examination" (as described above), passed at a relatively high level.

d. A "preliminary examination," consisting of two parts:
   i. a 3-hour written examination on the student's specialty;
   ii. an oral examination, given two weeks after the written part, emphasizing questions in the area where the student wishes to write a thesis.

The purpose of the preliminary examination is "to determine the fitness of the student for pursuing a doctoral program in the field in which a degree is desired."

e. A moderate level of proficiency in two foreign languages (normally two of the languages French, German, and Russian).

Proficiency may be demonstrated by scoring sufficiently well on certain standardized tests, performing satisfactorily in "foreign language seminars" regularly offered in the department, or passing a special reading examination administered by the Department of Foreign Languages and Literatures in cooperation with the Department of Pure and Applied Mathematics.

f. At least one semester of (supervised) teaching.

g. An internship (for students in applied mathematics). On-the-job experience in the middle of a doctoral program can be beneficial in many ways. Possible benefits include:

i. an opportunity for students to sample the type of career they are studying for, and to make sure they like it;

ii. exposure to the realities of nonacademic mathematical work, with resulting perspective on and motivation for further study;

iii. possible thesis problems;

iv. opportunities for employers to look over possible recruits for regular positions, and *vice versa.*

Ordinarily, each student, having completed approximately three years of graduate work, will have an "on-campus internship," which in one way or another will involve a regular commitment for perhaps a semester to working as a "junior mathematical consultant," for example in the Academic Services Unit (see Appendix F). Alternatively, it might take the form of working on a project contracted for this purpose with some firm or agency. The "on-campus internship" will serve as background for the "off-campus internship," a temporary position with some appropriate off-campus organization. Informal arrangements with a variety of governmental and private units indicate that positions of this kind will be available in ample variety and number.

h. A thesis. Students in applied mathematics are most likely to write on problems of a real-world character, involving the analysis and perhaps the construction of mathematical models of real phenomena. The thesis should contain work which is correct, original, and important—enough so to qualify it for publication in a research journal, though not necessarily a mathematics journal.

i. The final examination. In this oral examination the student, having completed the thesis and obtained approval of it from the thesis committee, defends it orally.

The hypothetical student whose program was given at the

end of section 1 of this appendix, if interested in going on for a doctorate, might continue as follows:

FIFTH SEMESTER
- Abstract Analysis (503)
- Electives in Mathematics, Statistics, Computer Science
- Science Elective

SIXTH SEMESTER
- Applied Functional Analysis (504)
- Electives
- On-Campus Internship
- Preliminary Examination (written and oral)

SUMMER FOLLOWING SIXTH SEMESTER
- Begin Off-Campus Internship (603)

SEVENTH SEMESTER
- Complete Off-Campus Internship (603)
- Thesis (800)

EIGHTH SEMESTER
- Elective(s)
- Thesis (800)
- Final Examination

APPENDIX B

VISITORS AND VISITED

1. *Visitors Supported by the Service-Oriented Options Grant*

a. W. L. Nicholson (May 1976). Dr. Nicholson, Battelle Pacific Northwest Laboratories, lectured on applied statistics and contributed richly to the definition of several options.

b. Kenneth Smith (September 1976-February 1977). Dr. Smith, interested especially in computer approaches to physical problems, offered a course in advanced numerical analysis for which he left a set of lecture notes. He also gave general lectures and advised on the future of computing at this university.

c. William O. Alltop (September 1976-June 1977). Dr. Alltop, whose usual affiliation is with the Naval Weapons Center at China Lake, was supported jointly from university and grant funds. His special contributions to the SOO Project were a seminar on coding theory (on which he is a widely recognized expert) which ran all year, and successive drafts for a possible option in discrete mathematics.

d. James A. Cochran (January-June 1977). Dr. Cochran was chosen because of his general mathematical reputation, his long experience at Bell Laboratories, and his recent leadership in developing an applied mathematics program at Virginia Tech. He gave a very well-received seminar on modeling using classical mathematics, for which he left behind a polished set of notes. He returned in the fall of 1978 to chair the department.

e. Darwin Klingman (May-June 1977). Dr. Klingman is a leading expert on computer implementation of network theory and is in great demand as a consultant to government and industry. He presented two general lectures and an intensive survey, in short-course form, of the best work in his area. He left behind a large number of reports, reprints, and copies of the transparencies he used.

f. William F. Lucas (September 1977-January 1978). Dr. Lucas, Professor of Applied Mathematics and Operations Research at Cornell University, was brought here primarily because of his wide acquaintance with "new" applied mathematics, especially as applied to the social sciences. He offered an excellent semester-long seminar on mathematical modeling and also gave numerous other lectures at Washington State University and neighboring institutions.

g. Ingram Olkin (March and May 1978). Professor Olkin, of the Department of Statistics at Stanford, gave six lectures on a variety of topics related to inequalities, probability, and applications, and advised the coordinating committee on the statistics options.

h. Gerald E. Nash (April-May 1978). Dr. Nash, of the Material Science and Technology Division, Naval Research Laboratory, gave one general talk and a sequence of more technical lectures on recent applications of mathematics in material science and metallurgy, for which he left a set of notes and transparencies.

i. Janet M. Myhre (May 1978). Dr. Myhre, who is Director of the Institute of Decision Science, Claremont Men's College, was invited not only to give a sequence of lectures in her specialty, statistics, but also to share her experiences in the Institute of Decision Science, which has succeeded in organizing educational research projects for students and faculty contracted with off-campus firms and agencies.

j. Hal Caswell (May 1978). Dr. Caswell, a member of the Biological Sciences Group at the University of Connecticut, is a leading mathematical biologist. He gave a general talk "On the interaction between the biologist and the mathematician" and a series of lectures on life history theory, and left a set of manuscript notes for the latter.

k. Norman Zabusky (May 1979). Dr. Zabusky was long at Bell Laboratories and is now at the University of Pittsburgh. His lectures included one for undergraduates on the general nature of industrial mathematics.

2. Other Visitors

Professor W. Robert Boland spent the period from September 1976 through July 1977 at Washington State University as an exchangee from Clemson. (Professor T. A. Newton, normally at Washington State University, spent the year at Clemson.) Besides teaching courses related to the project, he took a lively and constructive interest in the computing situation at Washington State University, and also began collaboration on research with Dr. Janusz Kowalik of Washington State University.

Short-term visitors who came to Washington State University for other purposes but kindly consented to be consulted about the project include:

Dr. Carl A. Bennett, Battelle Human Affairs Research Center

Professor Emeritus Z. W. Birnbaum, University of Washington

Tim Chambers, Naval Ship Weapon Systems Engineering Station, Port Hueneme, California

Professor Donald Cohen, California Institute of Technology

Dr. Albert Erisman, Boeing Computer Services, Seattle, Washington

Jack Futoran, Pacific Missile Test Center, Port Mugu, California

Walter C. Johnson, Bell Laboratories

Dr. Meredith Potter, Gradient Modeling, Inc., and Northwest Forest Fire Laboratory, Missoula, Montana

Dr. Jill Shapiro, Shapiro and Associates, Seattle, Washington

Dr. Lynn Wilson, Bell Laboratories

3. *Participants in Evaluation Meetings*

The following people attended at least one of the evaluation meetings (September 1975 and June 1978) at Washington State University:

Clayton Aucoin, Clemson University

Reta Borton, Claremont Graduate School

William E. Boyce, Rensselaer Polytechnic Institute

James A. Cochran, Virginia Polytechnic Institute and State University

Albert E. Erisman, Boeing Computer Services

John D. Fulton, Clemson University

Melvin Henrikson, Harvey Mudd College

Samuel L. S. Jacoby, Boeing Computer Services

John W. Kenelly, Clemson University

Murray S. Klamkin, University of Waterloo, now University of Alberta

Donald S. McArthur, Milliken & Co.

Robert McFadden, Northern Illinois University

Wesley L. Nicholson, Battelle Pacific Northwest Laboratories

Thomas G. Proctor, Clemson University

Robert M. Thrall, Rice University

Christoph Witzgall, National Bureau of Standards

D. E. Zilmer, Naval Weapons Center, China Lake

4. *Firms and Agencies Visited*

Each of the private firms and government agencies in the following list was visited in 1975-1979 by members of the Coordinating Committee of the Service-Oriented Options Project, in part or wholly for discussions with appropriate personnel about applied mathematics in general, and this project in particular.

Battelle Human Affairs Research Center, Seattle, Washington

Battelle-Northwest, Richland, Washington

The Boeing Company, Seattle, Washington

Boeing Computer Services, Seattle, Washington

Bonneville Power Administration, Portand, Oregon

Burroughs Corporation, Chicago, Illinois

CH_2M-Hill, Inc., Bellevue, Washington

Firemen's Fund Insurance, San Francisco, California

General Telephone Company of the Northwest, Everett, Washington

Hewlett-Packard, Cupertino, California

Illinois Bell, Chicago, Illinois

John Fluke Manufacturing Company, Inc., Mountlake Terrace, Washington

Mathematics Northwest, Bellevue, Washington

A. C. Nielsen Company, Northbrook, Illinois

Northwest Fisheries Center, Seattle, Washington

Pacific Car and Foundry, Seattle, Washington

Pacific Marine Environmental Laboratory, Seattle, Washington

Pacific Northwest Bell Telephone Company, Seattle, Washington

Pacific Telephone and Telegraph Company, San Francisco, California

Professional Computation Incorporated, Hayden Lake, Idaho

Rainier National Bank, Seattle, Washington

Sears, Roebuck and Company, Chicago, Illinois

Shapiro and Associates, Seattle, Washington

Snohomish County Public Utility District, Everett, Washington

Standard Oil of California, San Francisco, California

Standard Oil of Illinois, Chicago, Illinois

Tektronix, Inc., Beaverton, Oregon

U.S. Environmental Protection Agency, Seattle, Washington
U.S. General Accounting Office, Seattle, Washington
U.S. General Services Administration, Auburn, Washington
U.S. Geological Survey, Menlo Park, California
U.S. Geological Survey, Seattle, Washington
U.S. Geological Survey, Tacoma, Washington
Weyerhaeuser Lumber Company, Federal Way, Washington

APPENDIX C

RECENT WSU PUBLICATIONS AND THESES IN APPLIED MATHEMATICS

SELECTED FACULTY PUBLICATIONS

D. C. Barnes, "Asymptotic bounds for the eigenvalues of vibrating systems." J. Diff. Equ. *7*, 497-508 (1970).

K. Bergstresser, "Generalization of domination structures and nondominated solutions in multicriteria decision making." J. Optimization Theory and Appl. *18*, 3-13 (1976). [With A. Charnes and P. L. Yu.]

K. Bergstresser, "An energy conservation model for the Pacific Northwest." Planning and Management Systems (1979), in press. [With George Hinman and Walter Butcher.]

K. Bergstresser, "Domination structures and multicriteria problems in n-person games." Theory and Decision *8*, 5-48 (1977). [With P. L. Yu.]

J. A. Cochran, "Integral operators and an analogue of the Hausdorff-Young theorem." J. London Math. Soc. (2) *15*, 511-520 (1977). [With C. Oehring.]

J. A. Cochran, "Composite integral operators and nuclearity." Arkiv for Matematik *15*, 215-222 (1977).

M. A. Jacroux, "On the properties of proper (M,S) optimal block designs." Annals of Statistics, 1978.

Janusz Kowalik, "A nonlinear programming approach to a very large hydroelectric system optimization." Mathematical Programming *6*, 28-41 (1974). [Co-authored.]

Julie H. Lutz, "Cassegrain image scanner observations of emission lines in the spectra of planetary nebulae." P.A.S.P. *89*, 10-12 (1977).

Thomas E. Lutz, "On the use of trigonometric parallaxes for the calibration of luminosity systems: theory." Publ. Astron. Soc. Pac. *85*, 573-578 (1973). [With D. H. Kelker.]

Allan H. Marcus, "Traffic noise as a filtered Markov renewal process." J. Appl. Prob. *10*, 377-386 (1973).

Allan H. Marcus, "Moments of the exit time distribution for carboxyhemoglobin due to cigarette smoking." Adv. Appl. Prob. *15*, (1978), in press. [With S. Czajkowski.]

Allan H. Marcus, "Heat shock threshold estimation for fish eggs and larvae in a power plant cooling system." Proc.

First DOE Stat. Symp. (1978) (to appear).

Robert Mifflin, "An algorithm for constrained optimization with semismooth functions." Mathematics of Operations Research *2*, 191-207 (1977).

Robert Mifflin, "Semismooth and semiconvex functions in constrained optimization." SIAM Journal on Control and Optimization *15*, 959-972 (1977).

T. A. Newton, "Self-excited oscillations in friction." Naval Weapons Center Tech. Publ. #5522, 249-264 (1973).

T. A. Newton, "Two dimensional homogeneous quadratic differential systems." SIAM Review *20*, 120-138 (1978).

Sam C. Saunders, "The statistical analysis of stellar X-ray sources." Technometrics *15*, 341-351 (1973).

Sam C. Saunders, "On optimal inventory under stochastic demand with two supply options." SIAM J. Appl. Math. *32*, 293-305 (1977). [With A. S. Whittemore.]

Sam C. Saunders, "The reliability of structures subjected to fatigue under inspection and repair." *Applications of Statistics* (North Holland, 1977), 481-496.

David J. Wollkind, "A linear stability analysis of an interface in an isothermal phase transformation with a concentration-dependent diffusion coefficient." J. Appl. Physics *43*, 3663ff. (1972).

David J. Wollkind, "Exploitation in three trophic levels: an extension allowing intraspecies carnivore interaction." Amer. Natur. *110*, 431ff. (1976).

David J. Wollkind, "A mathematical model relevant to the representation of a temperature dependent predator-prey mite ecosystem on apples." Proc. First Int. Conf. Math. Mod. *4*, 2137ff. (1977). [With J. A. Logan.]

David J. Wollkind, "A stability analysis of a prototype moving boundary problem in heat flow and diffusion." Amer. Math. Monthly *86*, 175-186 (1979). [With D. B. Oulton and R. N. Maurer.]

DOCTORAL THESES (with date, name of thesis adviser)

James A. Beck, "A transform method applied to coupled harmonic oscillator type problems." (1968; Bushaw)

J. J. Colbert, "Optimal harvesting and control of biologically renewable resources." (1975; Wollkind)

Martin Dana, "General conditions for Lyapunov stability." (1971; Bushaw)

Gary A. Hewer, "Topics in stability theory." (1969; Bushaw)

Robert N. Maurer, "Stability and perturbation methods in the natural sciences." (1977; Wollkind)

David B. Oulton, "Investigations of secular equations relevant to linear stability analyses of metallurgical phenomena." (1976; Wollkind)

Sassan Raissi, "A nonlinear stability analysis of the melting of a dilute binary alloy." (1973; Wollkind)

John Uong, "Analysis of the life length of multiple-component coherent structures." (1978; Saunders)

APPENDIX D

COURSE DESCRIPTIONS

This list includes:

1. courses offered by the Department of Pure and Applied Mathematics for which graduate students in mathematics may receive credit;
2. courses offered by other departments mentioned elsewhere in this report.

Unless there is an indication to the contrary, each course carries three semester hours of credit. Courses established or considerably modified in connection with the Service-Oriented Options Project are marked with an asterisk. Each description is followed by identification, in parentheses, of a textbook recently used in the course, if any. For a more comprehensive course listing, see the WSU *Graduate Study Bulletin, 1979-81*, or the *General Bulletin, 1978-80*.

Section 3 of this appendix provides a condensed syllabus of the "core" courses Math 501 and 502.

1. DEPARTMENT OF PURE AND APPLIED MATHEMATICS

Astr 435 ASTRONOMY AND ASTROPHYSICS (prerequisites: multivariable calculus, ordinary differential equations) Advanced topics in modern astronomy and astrophysics.

Astr 538 TOPICS IN MODERN ASTROPHYSICS (prerequisite: ordinary differential equations) Problems of current astrophysical interest in the area of stellar atmospheres, stellar interiors, gaseous nebulae, the interstellar medium and galaxies. (Osterbrook, *Astrophysics of Gaseous Nebulae.*)

Astr 499 SPECIAL PROBLEMS (Variable credit).

Astr 600 SPECIAL PROJECTS OR INDEPENDENT STUDY (Variable credit).

Mathematics

Math 408 MATHEMATICS FOR ECONOMISTS (prerequisites: some linear algebra and calculus) Mathematical topics applicable to modern economic analysis and research.

Math 410 THEORY OF FUNCTIONS OF A COMPLEX

VARIABLE (prerequisites: multivariable calculus and ordinary differential equations) Cauchy's theorem, Taylor and Laurent series, calculus of residues, conformal mapping, special functions applied to engineering and physical sciences. (Brown, Churchill, and Verhey, *Complex Variables and Applications.*)

*Math 415 INTERMEDIATE DIFFERENTIAL EQUATIONS (prerequisite: elementary differential equations) Linear systems; qualitative theory (existence, uniqueness, stability, periodicity); boundary value problems; applications. (R. D. Driver, *Ordinary and Delay Differential Equations.*)

Math 417 INTRODUCTION TO SIMULATION (prerequisites: introductory statistics; FORTRAN) Model formulation, simulation languages, and analysis of results with selected applications.

Math 420 LINEAR ALGEBRA (prerequisite: elementary linear algebra) Advanced topics in linear algebra including similarity transformation, canonical forms, dual spaces, Hermitian matrices, bilinear forms. (Halmos, *Finite-Dimensional Vector Spaces.*)

Math 421 ALGEBRAIC STRUCTURES (prerequisite: elementary linear algebra) Properties of algebraic structures and their homomorphisms, semi-groups, groups, rings, unique factorization domains, fields. (Burton, *Introduction to Modern Abstract Algebra.*)

Math 425 INTRODUCTORY TOPOLOGY (prerequisites: multivariable calculus and ordinary differential equations) Sets, metric spaces, topological spaces, continuous mappings, compactness, connectedness, local properties, function spaces, fundamental groups. (R. A. Conover, *A First Course in Topology.*)

Math 440 APPLIED MATHEMATICS I (prerequisites: multivariable calculus and ordinary differential equations) Green's and Stokes' theorems, orthogonal functions, eigenvalue problems, Fourier series, applications involving partial differential equations and boundary value problems. (Kreyszig, *Advanced Engineering Mathematics.*)

Math 441 APPLIED MATHEMATICS II (prerequisite: Math 440) Partial differential equations and boundary value problems, transform methods, nonlinear differential equations. (Kreyszig, *Advanced Engineering Mathematics.*)

*Math 448 NUMERICAL ANALYSIS (prerequisites: FORTRAN; multivariable calculus, ordinary diferential equations) Interpolation and approximation, numerical quadrature, solution of linear systems of equations, nonlinear equations, solution of ordinary differential equations. (Dahlquist and Bjorck, *Numerical Methods.*)

Math 464 OPERATIONS RESEARCH AND GAME THEORY (prerequisite: multivariable calculus) Linear and integer programming, optimization problems, applications to economic and military strategies, rectangular games, mini-max theory. (K. G. Murty, *Linear and Combinatorial Programming.*)

Math 481 TOPICS IN ANALYSIS (prerequisite: advanced calculus) May be repeated for credit.

Math 500 PROSEMINAR (1 hour credit.)

•Math 501[1] LINEAR ALGEBRA AND ANALYSIS (5 hours credit; prerequisites: advanced calculus and Math 420) Advanced linear algebra, calculus on Euclidean n-space, basic complex analysis.

•Math 502[1] ANALYSIS (5 hours credit; prerequisite Math 501) Harmonic functions, metric spaces, integration, Hilbert spaces, Fourier series and integrals, Fourier and Laplace transforms, special functions, group representations.

•Math 503 ABSTRACT ANALYSIS (4 hours credit; prerequisite: Math 502) Topological structures, generalized measure and integration, basic functional analysis, function spaces, generalized functions, applications to numerical analysis. (Rudin, *Functional Analysis.*)

•Math 504 APPLIED FUNCTIONAL ANALYSIS (4 hours credit; prerequisite. Math 503) Applications of the techniques of Green's functions, spectral analysis, asymptotic expansions, and method of characteristics to differential equations. (Friedman, *Techniques of Applied Mathematics.*)

Math 505 ABSTRACT ALGEBRA AND ALGEBRAIC FUNCTIONS (4 hours credit; prerequisites: Math 421, 501) Groups, rings, fields, homological algebra, algebraic functions.

Math 507 ADVANCED THEORY OF NUMBERS Analytic and algebraic number theory.

Math 509 FOUNDATIONS OF MATHEMATICS The basis of mathematics in logic and set theory; continuum hypothesis, Godel's theorems, recent developments.

Math 512 ORDINARY DIFFERENTIAL EQUATIONS (prerequisite: advanced calculus) Existence of solutions, linear systems; qualitative behavior, especially stability; periodic solutions.

Math 525 TOPOLOGY I (prerequisites: advanced calculus, Math 421) General topology, homotopy, homology, manifolds. (Munkres, *Topology—A First Course.*)

[1]For a syllabus of Math 501-502, see item 3 at the end of this appendix.

Math 526 TOPOLOGY II (prerequisite: Math 525) Continuation of Math 525.

Math 539 GROUP REPRESENTATION THEORY AND APPLICATIONS (prerequisites: advanced physics or chemistry; Math 420) Group theory, matrix groups, group representations, and selected applications from physics and chemistry.

*Math 540 PARTIAL DIFFERENTIAL EQUATIONS I (prerequisite: advanced calculus) Partial differential equations and other functional equations; general theory, methods of solution, applications.

*Math 541 PARTIAL DIFFERENTIAL EQUATIONS II (prerequisite: Math 540) Continuation of Math 540.

*Math 544 COMPUTATIONAL LINEAR ALGEBRA (prerequisites: FORTRAN, elementary linear algebra) Numerical solution of linear systems of equations, linear least squares problems, matrix eigenvalue and eigenvector computation, error analysis. (Stewart, *Introduction to Matrix Computations.*)

*Math 545 ADVANCED NUMERICAL ANALYSIS (prerequisites: Math 448, 544) Theory of approximation, numerical integration of partial differential equations, advanced techniques in matrix calculus, and analysis of computational errors.

Math 550 ADVANCED TOPICS IN GEOMETRY Projective, affine, and non-Euclidean geometries and their relation to abstract algebra and differential geometry. (Raghararao, *Constructions and Combinatorial Problems in Design Experiments.*)

Math 551 GROUPS AND TOPOLOGICAL GROUPS (prerequisites: Math 421, 425) Group theory and theory of topological algebraic structures.

*Math 562 MATHEMATICAL GENETICS (prerequisites: genetics, Stat 443) Deterministic and stochastic approaches to genetics and population genetics, branching, birth-death, and diffusion process as applied to genetics. (Elandt-Johnson, *Probability Models and Statistical Methods in Genetics.*)

*Math 564 TOPICS IN OPTIMIZATION (prerequisites: advanced calculus, Math 544, FORTRAN) Advanced topics in the theory and computing methodology in optimization with emphasis on real-life algorithmic implications.

*Math 570 MATHEMATICAL FOUNDATIONS OF CONTINUUM MECHANICS I (prerequisites: advanced calculus and ordinary differential equations) The basic mathematical theory of continuum mechanics and its relation to perturbation techniques and stability methods. (Lin and Segel, *Mathematics Applied to Deterministic Problems in the Natural Sciences.*)

*Math 571 MATHEMATICAL FOUNDATIONS OF CON-

TINUUM MECHANICS II (prerequisite: Math 570) Continuation of Math 570.

Math 581 SEMINAR IN ANALYSIS

Math 582 SEMINAR IN ALGEBRA

*Math 583 SEMINAR IN APPLIED MATHEMATICS

Math 584 SEMINAR IN TOPOLOGY AND GEOMETRY

Math 585 SEMINAR IN NUMBER THEORY

*Math 586 TOPICS IN MATHEMATICAL MODELING IN NATURAL SCIENCES Special topics in the mathematical modeling of physical and biological phenomena.

Math 590 SEMINAR IN UNDERGRADUATE MATHEMATICS INSTRUCTION Curricular and other problems of teaching mathematics to undergraduates.

Math 591 SEMINAR IN THE HISTORY OF MATHEMATICS I (1 hour credit) Topics in the history of mathematics to 1800. (Boyer, *A History of Mathematics.*)

Math 592 SEMINAR IN THE HISTORY OF MATHEMATICS II (1 hour credit) Topics in the history of mathematics from 1800 to the present. (Boyer, *A History of Mathematics.*)

Math 600 SPECIAL PROJECTS OR INDEPENDENT STUDY (Variable credit)

Math 602 TEACHING INTERNSHIP (prerequisite: 40 hours of credit in DA program) A structured teaching internship of no less than one quarter nor more than an academic year.

*Math 603 SERVICE INTERNSHIP (prerequisite: 40 credit hours of graduate work in mathematics) A structured internship in a non-academic working environment for between six and twelve months.

Math 700 MASTER'S RESEARCH, THESIS, AND/OR EXAMINATION (Variable credit)

Math 702 MASTER'S SPECIAL PROBLEMS, DIRECTED STUDY, AND/OR EXAMINATION (Variable credit)

Math 800 DOCTORAL RESEARCH, DISSERTATION, AND/OR EXAMINATION (Variable credit)

Statistics

Stat 429 INTRODUCTION TO PROBABILITY AND DISTRIBUTION THEORY (prerequisite: some calculus) Elements of probability theory, binomial, Poisson, normal distributions, expectation, independence, transformations, estimation and tests of hypotheses as applied to problems of modern science. (Wal-

pole and Myers, *Probability and Statistics for Engineers and Scientists.*)

Stat 430 STATISTICS FOR PHYSICAL SCIENCE (prerequisite: Stat 429) Statistical analysis of experimental data using modern desk calculators, estimation, tests of hypotheses, regression analysis, least squares, chi-square methods. (Walpole and Myers, *Probability and Statistics for Engineers and Scientists.*)

Stat 443 APPLIED PROBABILITY (prerequisites: elementary linear algebra, calculus) Axioms of probability theory, random variables, expectation, generating function, law of large numbers, central limit theorem, Markov chains. (Sheldon Ross, *A First Course in Probability.*)

Stat 544 APPLIED STOCHASTIC PROCESSES (prerequisite: Stat 443) Poisson and Markov processes, queuing theory, auto-covariance, stationarity, power spectra, harmonic analysis, linear mean-square predictions. (Ross, *Applied Probability Models with Optimization Applications* and Hoels, Port, and Stone, *Introduction to Stochastic Processes.*)

Stat 548 STATISTICAL THEORY I (prerequisites: multivariable calculus, Stat 430) Probability spaces, combinatorics, multidimensional random variables, characteristic functions, special distributions, limit theorems, stochastic processes, order statistics. (Mood, Graybill, and Boes, *Introduction to Theory of Statistics.*)

Stat 549 STATISTICAL THEORY II (prerequisite: Stat 548) Continuation of Stat 548. Statistical inferences, estimation and testing hypotheses, regression analysis, sequential analysis and nonparametric methods. (Mood, Graybill, and Boes, *Introduction to Theory of Statistics.*)

Stat 560 MATHEMATICAL STATISTICS AND PROBABILITY THEORY (prerequisites: advance calculus, Stat 549) Distribution-free statistics, stochastic processes and Markov chains, measure theoretic foundations of probability. (Rozanov, *Stationary Random Processes.*)

*Stat 561 MATHEMATICAL STATISTICS AND PROBABILITY THEORY (prerequisite: Stat 429 or Stat 443) Continuation of Stat 560. The analysis of the strength and life of materials as applied to structures and coherent systems, maintenance models. (Barlow and Proschan, *Statistical Theory of Reliability and Life Testing: Probability Models.*)

*Stat 572 DATA ANALYSIS (prerequisites: elementary linear algebra, Stat 443 or Stat 548) Robust statistical methods resistant to failures of model assumptions; smoothing; curve-fitting; multivariable relationships; clustering. (Chatterjee and

Price, *Regression Analysis by Example* and Tulee and Mosteller, *Data Analysis and Regression.*)

2. OTHER DEPARTMENTS

Agricultural Economics

AgEc 512 ADVANCED TOPICS IN APPLIED PROBLEM ANALYSIS OF AGRICULTURAL ECONOMICS DATA Model construction and estimations for analysis of agricultural supply and demand problems.

Biometrics

Biom 520 EXPERIMENTAL DESIGN FOR RESEARCH (prerequisite: Stat 443) The design and analysis of experiments by linear models.

Business Administration

BA 444 DECISION ANALYSIS Introduction to Bayesian analysis, decision theory, utility, subjective probability and multiperson decision theory as applied to business.

BA 514 TECHNIQUES OF SAMPLING Sample surveys for business use; theory and application with emphasis on appropriate sample types and estimation of parameters.

BA 516 TIME SERIES Seasonal, cyclical, and trend analysis, index numbers; autoregressive, moving average and mixed models; model identification and forecasting.

BA 519 MULTIVARIATE ANALYSIS Multivariate normal distribution, estimation, hypothesis testing, discriminant analysis, canonical correlation, principal components, factor analysis.

BA 542 APPLIED STOCHASTIC MODELS Stochastic processes, Markov models, stochastic dynamic programming, queues and simulation applied to business problems.

BA 560 RESEARCH METHODOLOGY Types of data needed and available, collection and analysis of data as they relate to decisional research.

Chemistry

Chem 533 THERMODYNAMICS Fundamental theory and applications.

Computer Science

Cp S 400 DESIGN AND ANALYSIS OF ALGORITHMS

Analysis of data structures and algorithms, computational complexity and design of efficient data-handling procedures.

Cp S 516 THEORY OF COMPUTING Discrete structures, automata, formal languages, recursive functions, theory of algorithms and computability.

Cp S 517 AUTOMATA THEORY Sequential machines, finite automata, pushdown automata.

Cp S 520 ADVANCED TOPICS IN INFORMATION PROCESSING

Cp S 540 INFORMATION STORAGE AND RETRIEVAL Theory and practice in the storage and retrieval of information, file organization, file search, document and fact retrieval, hardware, system design.

Economics

Econ 510 MATHEMATICAL MODELS OF ECONOMICS Exposition of the mathematical structure of economic theories, the unity of mathematical theorems and underlying model developments.

Econ 511 ECONOMETRICS Use of mathematical, economic and statistical research as a means of testing economic theories.

Environmental Science

Env S 510 MODELING AND SIMULATION OF ECOLOGICAL SYSTEMS.

Mechanical Engineering

M E 538 COMBUSTION General combustion phenomena, chemical reactions, combustor modeling, laminar and turbulent flame theory, emissions.

Physics

Phys 572 INTRODUCTION TO THEORETICAL PHYSICS Mathematical principles of theoretical physics, generalized functions, Fourier Transforms, operators in Hilbert space.

Psychology

Psych 513 SEMINAR IN QUANTITATIVE PSYCHOLOGY

Sociology

Soc 430 WORLD POPULATION: ISSUES AND DEBATES Population study and relation to other fields of inquiry, causes

and effects of changes in fertility, morality, migration and urbanization.

Soc 530 DEMOGRAPHY Advanced demography, relation to other fields, economic and social determinants of fertility, mortality, migration, and urbanization.

Zoology

Zoo 534 MATHEMATICAL MODELING OF BIOLOGICAL SYSTEMS Physical principles and mathematical models applied to analysis of biological problems.

3. SYLLABUS FOR MATH 501-502 AS OF 1978-1979

Math 501-502 is an integrated course on core mathematics for entering graduate students and is required of all graduate students in the department. It meets five days a week for a full academic year and has been taught from notes produced in the department and distributed to the students. The coverage is modified somewhat from year to year. The following abbreviated syllabus indicates the coverage intended for the year 1978-1979.

Preliminaries. Logical and set-theoretic notations; the axiom of choice; groups and fields.

Metric spaces. Basic concepts; subspaces, continuity, compactness, connectedness, products; completeness and completion; Baire category; Banach contraction principle.

Linear spaces. Linear independence and bases; quotients; complexification; normed and inner product spaces; orthogonality.

Linear operators. Matrices; bounded operators; Riesz representation theorem; normal, Hermitian, positive, skew, and unitary transformations; linear equations.

Multilinear operators. Tensors; determinant functions; trace and characteristic equation.

The Jordan form.

Differential calculus. Differential; gradient; directional derivatives; mean value theorem; inverse and implicit function theorems; Taylor's theorem; vector analysis.

Integration on manifolds. Manifolds; differential forms; Stokes' theorem.

Complex analysis. Differentiation; power series; elementary functions; Cauchy theory; local properties; singularities; residue calculus; argument principle. Rouche's theorem. Schwarz's

lemma; the Riemann sphere; Mobius transformations and conformal mapping.

Harmonic functions. Elementary properties; Dirichlet's problem; Green's functions.

Lebesgue measure and integration. Step functions; measure zero; Lebesgue integral; convergence theorems; relation to Riemann integral; indefinite integrals; Fubini's theorem; measure; L_p spaces.

Special function. The gamma function; orthogonal polynomials; Bessel functions; Arzela-Ascoli and Stone-Weierstrass theorems.

Fourier analysis. Fourier series. Fourier integral. Laplace transform.

APPENDIX E

FACULTY

1. REGULAR MATHEMATICS FACULTY.

This list includes all people now (May 1979) expected to be holding regular appointments in the faculty of the Washington State University Department of Pure and Applied Mathematics in the academic year 1979-1980. The number at the end of each entry indicates the year that the person joined the Department.

David C. Barnes, Associate Professor (Ph.D., University of California, Davis, 1967). Classical analysis, eigenvalue problems (1966).

Kenneth E. Bergstreser, Assistant Professor (Ph.D., University of Rochester, 1975). Operations research, optimization, multicriteria problems, game theory (1974).

Kenneth A. Bush, Professor (Ph.D., University of North Carolina, 1950) Statistics, combinatorics, mathematical economics (1961).

Donald W. Bushaw, Professor (Ph.D., Princeton University, 1952). Ordinary differential equation, analysis of set-valued functions, university mathematics education (1952).

James A. Cochran, Professor and Chairman (Ph.D., Stanford University, 1962). Electromagnetic theory, special functions, asymptotics, differential and integral equations, operator theory (1978).

William M. Cunnea, Associate Professor (Ph.D., University of California, Berkeley, 1962). Alegbra, algebraic geometry, multiplicative lattice theory (1961).

Duane W. DeTemple, Associate Professor (Ph.D., Stanford University, 1970). Complex analysis (1970).

Michael A. Jacroux, Assistant Professor (Ph.D., Statistics, Oregon State University, 1976). Experimental design, optimal experimental design, estimation in linear and nonlinear models (1979).

Roy A. Johnson, Associate Professor (Ph.D., University of Iowa, 1964). Measure theory, especially product measures and measures in locally compact spaces (1966).

James H. Jordan, Professor (Ph.D., University of Colorado, 1962). Number theory, mathematics education (1962).

Michael J. Kallaher, Professor (Ph.D., Syracuse University, 1967). Algebra, combinatorics, finite geometry (1969).

Darrell C. Kent, Professor (Ph.D., University of New Mexico, 1963). General topology, convergence structures (1963).

Janusz Kowalik, Professor, Director of Systems and Computing (Ph.D., Polish Academy of Sciences, 1961). Numerical analysis, optimization, simulation (1974).

Jan E. Kucera, Professor (Ph.D., Charles University, 1966). Control theory, distribution theory (1970).

Calvin T. Long, Professor (Ph.D., University of Oregon, 1955). Elementary and combinatorial number theory, mathematics education (1956).

Norman Y. Luther, Associate Professor (Ph.D., University of Iowa, 1963). Measure theory (1964).

Julie H. Lutz, Associate Professor (Ph.D., University of Illinois, 1971). Astronomy (1971).

Thomas E. Lutz, Associate Professor (Ph.D., University of Illinois, 1969). Application of statistical and data analysis methods to astronomy (1969).

Allan H. Marcus, Professor (Ph.D., University of California, Berkeley, 1965). Stochastic processes, models, multivariate data analysis and statistical computing, environmental toxicology and standards, health effects of pollutants (1977).

Kelly McKennon, Professor (Ph.D., University of Washington, 1969). Harmonic analysis (1970).

Robert Mifflin, Associate Professor (Ph.D., Operations Research, University of California, Berkeley, 1971). Optimization, especially nonsmooth optimization (1979).

Tyre A. Newton, Professor (Ph.D., University of Georgia, 1952). Analysis, differential equations, operational mathematics, analog and hybrid simulation (1958).

Theodore G. Ostrom, Professor (Ph.D., University of Minnesota, 1947). Finite projective planes (1960).

Jack M. Robertson, Professor (Ph.D., University of Utah, 1964). Topology, mathematics education (1964).

Sam C. Saunders, Professor (Ph.D., University of Washington, 1956). Statistics (1971).

William A. Webb, Associate Professor (Ph.D., Pennsylvania State University, 1968). Number theory (1969).

H. Clare Wiser, Professor (Ph.D., University of Utah, 1961). Differential equations (especially physical and biological applications), mathematics education, topology (1969).

David J. Wollkind, Associate Professor (Ph.D., Rensselaer Poly-

technic Institute, 1968). Fluid and continuum mechanics, asymptotic perturbation and stability methods, metallurgical and ecological phenomena (1970).

2. WASHINGTON STATE UNIVERSITY FACULTY MEMBERS, NOT IN MATHEMATICS, WHO HAVE CONTRIBUTED TO THE PROJECT.

In most instances, contributions took the form of participation in meetings to discuss general directions and specific courses and curricula. Some people listed here did considerably more. The list is an indication of the breadth and diversity of support for the Service-Oriented Options Project within the University.

Richard A. Baker (Electrical Engineering)
Nathaniel Beck (Political Science)
Allan A. Berryman (Entomology)
Leroy Blakeslee (Agricultural Economics)
Thomas P. Bogyo (Statistical Services)
Walter R. Butcher (Agricultural Economics)
Lewis F. Carter (Sociology)
William C. David (Veterinary Microbiology and Pathology)
James Egan (Psychology)
Millard Hastay (Economics)
Dale Hockstra (Business Administration)
Ronald A. Hopkins (Psychology)
Philip Kuhn (Sociology)
Gene A. Lawrence (Electrical Engineering)
Sherman C. Lowell (Physics)
George Marsaglia (Computer Science)
Sidney W. Miller (Career Services and Placement)
Charles B. Millham (Computer Science)
David Myers (Sociology)
Carl J. Nyman (Graduate School)
Richard A. Parker (Zoology, Computer Science)
Harriet B. Rigas (Electrical Engineering, Academic Services)
Thomas S. Russell (Statistical Services)
R. Shane Ryland (History)
Arnold C. Satterthwait (Anthropology, Computer Science)
Vincent Schultz (Zoology)
David Stronck (General Biology)

John Tarnai (Experimental Education Program, Alcoholism Studies)

Min Chiang Wang (Business Administration)

John M. Wardwell (Sociology, Rural Sociology)

Donald A. West (Agricultural Economics)

Gerald L. Young (Environmental Science)

Ahmed S. Zaki (Business Administration)

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APPENDIX F

ACADEMIC SERVICES UNIT

In 1973 Washington State University's Office of Systems and Computing and Department of Pure and Applied Mathematics formed an Academic Services Unit. This somewhat unusual unit is expected to play an important role in the arrangement of on-campus internships for students in applied mathematics, so a brief description seems appropriate here.

The units was formed in response to the increasing use of mathematical models and computers in current research and teaching, and the consequent advancing sophistication of mathematical techniques. It provides consultation and assistance to research workers and educators at Washington State University. It has participating staff scientists from several disciplines including Computer Science, Mathematics, Physics, Engineering, and Statistics. These personnel, broadly experienced in applications, are available for use by the whole academic community in the pursuit of its research and educational goals.

Specific purposes of the Academic Services Unit include:

1. to assist in initiating research projects or proposals which have a considerable computational or mathematical content;
2. to participate in interdisciplinary and interdepartmental research projects requiring mathematical modeling, system analysis, advanced computational techniques, and use or development of sophisticated computer programs;
3. to provide expert staff programming assistance and advice to faculty and students;
4. to assist Computing Center users in the "debugging" of programs submitted for runs on our computer facilities and to alleviate the scarcity of information on available programs and data sets;
5. to inform Washington State University faculty members and researchers about up-to-date computer software, programming languages, and mathematical and computational methodology by organizing short courses and individual presentations;
6. to implement new efficient software packages, such as programming algorithms for the benefit of the computer user;

7. to implement and improve, in cooperation with educators, computer-assisted courses.

Academic Services provides user consulting on computing problems to the academic community. These users include students (other than those taking 200 level Computer Science classes), faculty, and staff members using the Computing Center for academic applications.

Staff assistants are available in the Consultants Office. They are prepared to give detailed support to users with problems with JCL, programming languages, and a number of programmin packages available at Washington State University. This service is provided free on a walk-in basis or by phone. Consultants are also prepared to give aid in debugging program logic and assisting in finding solutions to user problems. This may entail simply pointing the user to a canned program already on the system or evaluating actual computing needs and directing the user through the proper channels to the best solution. In short, the consultants are prepared to answer all questions the user may have on obtaining the best use of available computing dollars.

The Academic Services Unit is associated not only with the University's Computing Center, where the hardware is digital, but also with a Hybrid Facility.

Many on-campus internships for students in applied mathematics programs are expected to take the form of apprenticeships to the experienced consultants in the Academic Services Unit. In this way the interns will not only gain experience in the arts of mathematical and computational consulting but will also perform a valuable service to the university.

As a result of a reorganization effective July 1, 1979, the Academic Services Unit ceases to exist as a separate entity. Most of its functions are being absorbed by a new unit called University Computing Services, and *all* functions previously performed by Academic Services will continue to be available on campus.

PART IV. BIBLIOGRAPHY

This bibliography consists of two sections.

Section A lists some of the articles and reports concerning applied mathematics education that have come to the attention of participants in the Clemson and Washington State projects. Among other things, they report on related projects at other institutions.

Section B is a collection of sources of information on modern applied mathematics, with emphasis on modeling. This list was compiled from suggestions made by participants in the Conference on Experiential Applied Mathematics Education at Harvey Mudd College (May 31-June 2, 1979) and is reproduced here with permission.

A. APPLIED MATHEMATICS EDUCATION

Beaumont, C. F. A., and Wieser, R. J. "Co-operative programmes in mathematical sciences at the University of Waterloo." Journal of Co-operative Education *11*, 68-72 (1975).

Bowen, K. C. "The scope of mathematics in operational research." The Institute of Mathematics and its Applications Bulletin *8*, 78-84 (1972).

"Case studies: some mathematicians with nonacademic employment." Notices of the American Mathematical Society *21*, 346-348 (1974); *22*, 100-102, 181-184, 241-242, 355-356 (1975); *25*, 115-118 (1978).

"The changing role of the master's degree." Notices of the American Mathematical Society *23*, 206-209 (1976). [Panel discussion at the AMS meeting in San Antonio, January 1976.]

"Clemson conference on graduate programs in the applied mathematical sciences." CBMS Newsletter *12*, 59-60 (1977).

Committee of Presidents of Statistical Societies. *Careers in Statistics*. American Statistical Association, n.d.

Coulson, C. A. "Mathematics and the real world." The Institute of Mathematics and its Applications Bulletin *9*, 2-7 (1973).

Education Committee, Operations Research Society. *Careers in Operations Research*. n.d.

"Education in applied mathematics. Proceedings of a conference sponsored by Society for Industrial and Applied Mathe-

matics . . ." SIAM Review *9*, 289-415 (1967). [Papers by C. C. Lin, G. F. Carrier, R. Gomory, et al.]

"Employers' viewpoint on nonacademic employment: a panel discussion." Notices of the American Mathematical Society *25*, 184-188 (1978). [Account of a panel discussion at the annual meeting of the AMS in Atlanta, January, 1978.]

Fleming, Wendell H. "Nonacademic employment of Ph.D.'s in the mathematical sciences." Notices of the American Mathematical Society *22*, 152-155 (1975).

Gaskell, R. E. "Some realities for mathematicians, present and future." CBMS Newsletter *8*, no. 4, 1-4 (1973).

Gaskell, R. E., and Klamkin, M. S. "The industrial mathematician views his profession: a report of the Committee on Corporate Members." American Mathematical Monthly *81*, 699-716 (1974).

Hilton, Peter. "The new emphasis on applied mathematics." CBMS Newsletter *10*, 17-19 (1975).

Kapur, J. N. "Mathematical models in biology and medicine." The Mathematics Student *41*, 225-242 (1972). [Introductory talk at Symposium on Biomathematics at Bhopal, India, in 1972. This paper is followed by several papers on specific models.]

Klamkin, Murray S. "On the teaching of mathematics so as to be useful." Educational Studies in Mathematics *1*, 126-160 (1968).

Klamkin, Murray S. "On the ideal role of an industrial mathematician and its educational implications." American Mathematical Monthly *78*, 53-76 (1971). [This article includes a bibliography of 89 items.]

Mathematical Association of America, *Professional Opportunities in Mathematics*, 10th ed. (1978).

"The mathematical training of the nonacademic mathematician." SIAM Review *17*, 541-557 (1975). [Proceedings of a symposium at Rensselaer Polytechnic Institute with statements by George Handelman, Burton H. Colvin, et al.]

Nesbitt, Cecil J. "Actuarial careers for mathematicians." Notices of the American Mathematical Society *22*, 286-288 (1975).

"Nonacademic employers of Ph.D. mathematicians." Notices of the American Mathematical Society *26*, 198 (1979).

Pool, James C. T. "Applied mathematical sciences at the Department of Energy." CBMS Newsletter *13*, 49-50 (1978).

Raisbeck, Gordon. "Some reflections of a consulting mathe-

matician on academic mathematics." CBMS Newsletter *11*, 17-18 (1976).

"The role of applications in Ph.D. programs in mathematics." Notices of the American Mathematical Society *23*, 158-164 (1976). [Texts of talks given by a panel at the AMS meeting in Kalamazoo, August 1975.]

Seidman, T. I. "A proposal for a professional program in mathematics." American Mathematical Monthly *82*, 162-167 (1975).

Spanier, Jerome. "Academic realism: an innovative approach." SIAM News *9*, no. 3, 1-2 (June 1976).

Spanier, Jerome. "The mathematics clinic: an innovative approach to realism within an academic environment." American Mathematical Monthly *83*, 771-775 (1976).

Tucker, Alan. "Toward a mathematics major for the 1980's." American Mathematical Monthly *81*, 891-899 (1974).

Wagner, Daniel H. "Mathematicians in operations research consulting." American Mathematical Monthly *82*, 895-905 (1975).

Wyman, Max, chairman. "Panel discussion on mathematics in the university and in industry." *Proceedings of the Fourth Canadian Mathematical Congress*, 56-65 (1959).

Young, Gail S. "Graduate education and manpower in the mathematical sciences." CBMS Newsletter *10*, 49-53 (1975).

Zadeh, Lotfi A. "Mathematics—a call for reorientation." CBMS Newsletter *7*, no. 3, 1-3 (1972).

B. MATHEMATICAL MODELING

Andrews, J. G., and McLone, R. C., eds. *Mathematical Modelling*. Butterworths, 1976.

Aris, R. *Mathematical Modelling Techniques*. Pitman, 1978.

Bailey, N. T. J. *The Mathematics of Infectious Diseases*. (2nd ed.) Hafner Press, 1975.

Bartlett, M. S. *Stochastic Population Models*. Methuen, 1960.

Baumol, W. J. *Economic Theory and Operations Analysis*. (3rd ed.) Prentice Hall, 1972.

Bender, E. A. *An Introduction to Mathematical Modeling*. Wiley, 1978.

Brams, Steven. *Game Theory and Politics*. The Free Press, 1975.

Brand, L. E. *Vector Analysis*. Wiley, 1957. [Chapters 6, 7, 8.]

Braun, M. *Differential Equations and Their Applications*. Springer, 1975.

Clark, C. W. *Mathematical Bioeconomics*. Wiley, 1976.

DiPrima, R., ed. *Modern Modelling of Continuous Phenomena*. American Mathematical Society, 1977.

Feynman, R. P., Leighton, R. B., and Stands, M. *The Feynman Lectures on Physics. Vols. I, II, III*. Addison-Wesley, 1963-65.

Fishburn, Peter. *The Theory of Social Choice*. Princeton University Press, 1973.

Gale, D. *The Theory of Linear Economic Models*. McGraw-Hill, 1960.

Gaver, D. P., and Thopmson, G. L. *Programming and Probability Models in Operations Research*. Brooks/Cole, 1973.

Gold, H. J. *Mathematical Modelling of Biological Systems—An Introductory Guidebook*. Wiley, 1977.

Goldberg, Samuel, ed. *Undergraduate Mathematics in the Social Sciences*. Mathematical Association of America, 1978.

Grossman, S., and Turner, J. E. *Mathematics for the Biological Sciences*. MacMillan, 1974.

Haberman, R. *Mathematical Models*. Prentice-Hall, 1977.

Intriligator, Michael D. *Mathematical Optimization and Economic Theory*. Prentice-Hall, 1971.

Kaufmann, A., and Faure, R. *Introduction to Operations Research*. Academic Press, 1968.

Kenschaft, Patricia C. *Linear Mathematics: A Practical Approach*. Worth Publishing, Inc., 1978.

Khurgin, Y. *Did You Say Mathematics?* Mir Publishers, 1974.

Lin, C. C., and Segel, L. A. *Mathematics Applied to Deterministic Problems in the Natural Sciences*. MacMillan, 1974.

Lotka, A. J. *Elements of Mathematical Biology*. Dover, 1956.

Ludwig, Donald. *Stochastic Population Theories*. Springer, 1974.

MacArthur, R. M. *Geographical Ecology*. Harper & Row, 1972.

Maki, D. P., and Thompson, M. *Mathematical Models and Applications (with Emphasis on the Social, Life and Management Sciences)*. Prentice-Hall, 1973.

Maki, D. P., and Thompson, M. *Mathematical Models in the Undergraduate Curriculum*. Proceedings of a conference at Indiana University, 1975.

May, Robert. *Stability and Complexity in Model Ecosystems*. Princeton, 1973.

Maynard-Smith, John. *The Evolution of Sex*. Cambridge University Press, 1978.

Maynard Smith, John. *Models in Ecology*. Cambridge University Press, 1974.

Miller, Kenneth S. *Partial Differential Equations in Engineering Problems*. Prentice-Hall, 1964.

Olinik, Michael. *An Introduction to Mathematical Models in the Social and Life Sciences*. Addison-Wesley, 1978.

Pielou, E. C. *Mathematical Ecology*. (2nd ed.) Wiley, 1977.

Pollard, H. *Mathematical Introduction to Celestial Mechanics*. Mathematical Association of America, 1977.

Pollard, J. H. *Mathematical Models for the Growth of Human Populations*. Cambridge University Press, 1973.

Popev, E. M. *Mechanics of Materials*. Prentice-Hall, 1952.

Poston, T., and Stewart, I. *Catastrophe Theory and Its Applications*. Pitman, 1978.

Restle, F., and Greeno, J. *Introduction to Mathematical Psychology*. Addison-Wesley, 1970.

Roberts, F. S. *Discrete Mathematical Models*. Prentice-Hall, 1976.

Saaty, T. L. *Thinking with Models*. AAAS Study Guides on Contemporary Problems, No. 9, 1974.

Schwarz, R. J., and Friedland, B. *Linear Systems*. McGraw-Hill, 1965.

Stobodkin, L. *Growth and Regulation of Animal Population*. Holt, Rinehart & Winston, 1961.

Sloyer, C. W. *Fantastiks of Mathematics*. Notes available from C. W. Sloyer, University of Delaware.

Spiegel, M. R. *Applied Differential Equations*. (2nd ed.) Prentice-Hall, 1967.

Stoker, J. J. *Nonlinear Vibrations in Mechanical and Electrical Systems*. Interscience Publications, Inc., 1959.

Thompson, Maynard, ed. *Case Studies in Applied Mathematics*. Mathematical Association of America, 1976.

Thompson, Maynard, ed. *Discrete Mathematics and Its Applications*. Proceedings of a conference at Indiana University, 1976.

Thrall, R. M., et al. *Some Mathematical Models in Biology*. University of Michigan, 1967.

Tucker, A. C. *Applied Combinatorics*. (*Preliminary edition*). Wiley, 1978.

Wagner, H. M. *Principles of Operations Research with Applications to Managerial Problems*. Prentice-Hall, 1969.

Waltman, Paul. *Deterministic Threshold Models in the Theory of Epidemics*. Springer-Verlag, 1974.

Mathematical Models for Environmental Problems. Proceedings of the International Conference at the University of Southampton, 1976.

Proceedings of the Pittsburgh Conference on Modeling and Simulation, Vol. 1-9, Instrument Society of America, 1969-78.

Proceedings of the Summer Conference for College Teachers on Applied Mathematics. University of Missouri-Rolla, 1971.

SIAM Review. (All issues.)

Studies in Mathematical Biology, Parts I & II. MAA, MAA Studies in Mathematics, V. 15, 16., 1978.

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